“Investigar los Aspectos Holísticos y Parciales de la Gestión e Ingeniería de los Recursos Hídricos”

“Investigate the Holistic and Partial Aspects of Water Resources Management and Engineering”

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Abedin Mohammad Hosseinpour

La Tesis Doctoral titulada "Investigar los Aspectos Holísticos y Parciales de la Gestión e Ingeniería de los Recursos Hídricos", presentada por Abedin Mohammad Hosseinpour, se engloba dentro de la líneas de investigación correspondiente al Programa de Doctorado "Ingeniería de Sistemas Hídricos", en concreto dentro del desarrollo y mejora de Gestión integrada y gobernanza del agua y del medio ambiente, Soluciones Basadas en la Naturaleza para la Ingeniería Civil y Cambio Climático, sostenibilidad, agua y agricultura en el siglo XXI.

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Dr. JOSÉ LUIS MOLINA GONZÁLEZ

Lista de Publicaciones

La presente tesis doctoral consiste en un compendio de tres artículos científicos publicados en revistas internacionales de alto índice de impacto que se enumeran a continuación:

1. *"Interaction between gravel mining pits and river curvature on maximum scour depth through 2D hydraulic modelling"*
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Journal of Hydrology, Volume 604, January 2022.
Doi: 10.1016/j.jhydrol.2021.127245

2. *"Improving the Sustainability of Urban Water Management through Innovative Groundwater Recharge System (GRS)"*
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Sustainability, Volume 14, May 2022.
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3. *"HyetoClust method: Hyetograph design through Cluster Analysis"*
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[Trinity] "Neo, No One Has Ever Done Anything Like This."
[Neo] "That's Why It's Going To Work."

The Matrix, 1999

Agradecimientos

Contenido

Contents Page

Capítulo 1 “INTRODUCCIÓN”

1.1. Introducción

The water cycle is often taught as a simple circular cycle of evaporation, condensation, and precipitation. Although this can be a useful model, the reality is much more complicated. The paths and influences of water through Earth's ecosystems are extremely complex and not completely understood.

The water cycle shows the continuous movement of water within the Earth and atmosphere and includes many different processes. Perhaps the most important parts for humans, as have direct impacts on their lives, are rainfall and runoff where water vapor, condenses to form clouds, and precipitates back to earth in the form of rain and snow and then Liquid water flows across land (runoff), into the ground (infiltration and percolation), and through the ground (groundwater).

Water cycle management is a multidisciplinary approach relating to all planning, development, operational and tactical decisions to influence the water cycle. Most importantly water cycle management is used to ensure availability of clean water for designated use, and to ensure safe release of treated water back to nature. In an undisturbed environment water is in a natural cycle and it is generally usable for most of nature as it is in each stage of the cycle; and usually it is following human interaction that the natural cycle is disturbed.

Humans use water for drinking, industrial applications, irrigating agriculture, hydropower, waste disposal, and recreation. It is important that water sources are protected both for human uses and ecosystem health. In many areas, water supplies are being depleted because of population growth, pollution, and development. These stresses have been made worse by climate variations and man-made changes. Water resource management is a subset of water cycle management that focuses on utilization of freshwater resources.

Water is also the key part of extreme events such as drought and floods. Its abundance and timely delivery are critical for meeting the needs of society and ecosystems. Floods are a natural part of the water cycle, but they can be terrifying forces of destruction. Thus, floods are an area of study of hydrology and hydraulics and are of significant concern in agriculture, civil engineering, and public health. Human changes to the environment often increase the intensity, frequency and impacts of flooding, for example land use changes such as deforestation, large fires, and removal of sediments from riverbeds, changes in waterway course or flood controls such as with levees, and larger environmental issues such as climate change and sea level rise.

Among all these, rivers mostly considered as the most important water body and therefore its changes have become of high importance. The morphology of a river channel is a function of a number of processes and environmental conditions, including the composition and erodibility of the bed and banks (e.g., sand, clay, bedrock); erosion comes from the power and consistency of the current, and can affect the formation of the river's path. Also, vegetation and the rate of plant growth; the availability of sediment; the size and composition of the sediment moving through the channel; the rate of sediment transport through the channel and the rate of deposition on the floodplain, banks, bars, and bed; and regional aggradation or degradation due to subsidence or uplift. River morphology can also be affected by human interaction, which is a way the river responds to a new factor in how the river can change its course. An example of human induced change in river morphology is gravel mining from riverbed, which alters the flow of fluvial water and sediment. A river regime is a dynamic equilibrium system, which is a way of classifying rivers into different categories. It is also worth mentioning that river plans could have been in different forms from straight canal to sinusoidal and braided. Water engineering is another subset of water cycle management that focuses on these issues.

In conclusion, these parts have been the focus of studies by water scientists and engineers in order to Expand our knowledge at global and local scales in order to improve our ability to forecast weather, climate, analyze and manage water resources, understanding geology and morphologic changes, and evaluate environmental impacts and ecosystem health; As in this thesis, the research plan aimed to shine light on some dark parts of the water sciences.

The Above Paragraphs In Spanish:

El ciclo del agua a menudo se enseña como un ciclo circular simple de evaporación, condensación y precipitación. Aunque éste puede ser un modelo útil, la realidad es mucho más complicada. Los caminos y las influencias del agua a través de los ecosistemas de la Tierra son extremadamente complejos y no se comprenden completamente.

El ciclo del agua muestra el movimiento continuo del agua dentro de la Tierra y la atmósfera e incluye muchos procesos diferentes. Quizás las partes más importantes para los humanos, ya que tienen impactos directos en sus vidas, son las precipitaciones y la escorrentía, donde el vapor de agua se condensa para formar nubes y precipita hacia la tierra en forma de lluvia y nieve y luego el agua líquida fluye a través de la tierra (escorrentía).), hacia el suelo (infiltración y percolación) y a través del suelo (agua subterránea).

La gestión del ciclo del agua es un enfoque multidisciplinario relacionado con todas las decisiones de planificación, desarrollo, operativas y tácticas para influir en el ciclo del agua. Lo más importante es que la gestión del ciclo del agua se utiliza para garantizar la disponibilidad de agua limpia para el uso designado y para garantizar la liberación segura del agua tratada a la naturaleza. En un entorno tranquilo, el agua se encuentra en un ciclo natural y generalmente es utilizable para la mayor parte de la naturaleza, tal como lo es en cada etapa del ciclo; y normalmente es después de la interacción humana que se altera el ciclo natural.

Los seres humanos utilizan el agua para beber, para aplicaciones industriales, para irrigar la agricultura, para generar energía hidroeléctrica, para eliminar desechos y para recreación. Es importante que las fuentes de agua estén protegidas tanto para usos humanos como para la salud de los ecosistemas. En muchas zonas, los suministros de agua se están agotando debido al crecimiento demográfico, la contaminación y el desarrollo. Estas tensiones se han visto agravadas por las variaciones climáticas y los cambios provocados por el hombre. La gestión de los recursos hídricos es un subconjunto de la gestión del ciclo del agua que se centra en la utilización de los recursos de agua dulce.

El agua también es la parte clave de eventos extremos como sequías e inundaciones. Su abundancia y entrega oportuna son fundamentales para satisfacer las necesidades de la sociedad y los ecosistemas. Las inundaciones son una parte natural del ciclo del agua, pero pueden ser fuerzas de destrucción aterradoras. Por tanto, las inundaciones son un área de estudio de la hidrología y la hidráulica y son de gran preocupación en la agricultura, la ingeniería civil y la salud pública. Los cambios humanos en el medio ambiente a menudo aumentan la intensidad, la frecuencia y los impactos de las inundaciones, por ejemplo cambios en el uso de la tierra como la deforestación, grandes incendios y remoción de sedimentos de los lechos de los ríos, cambios en el curso de los cursos de agua o controles de inundaciones como los diques, y mayores impactos ambientales. cuestiones como el cambio climático y el aumento del nivel del mar.

Entre todos estos, los ríos se consideran en su mayoría como el cuerpo de agua más importante y, por lo tanto, sus cambios se han vuelto de gran importancia. La morfología del canal de un río es función de una serie de procesos y condiciones ambientales, incluida la composición y erosionabilidad del lecho y las orillas (por ejemplo, arena, arcilla, lecho de roca); La erosión proviene de la fuerza y consistencia de la corriente, y puede afectar la formación del cauce del río. Además, la vegetación y la tasa de crecimiento de las plantas; la disponibilidad de sedimentos; el tamaño y composición del sedimento que se mueve a través del canal; la tasa de transporte de sedimentos a través del canal y la tasa de deposición en la llanura aluvial, bancos, barras y lecho; y agradación o degradación regional debido a hundimiento o levantamiento. La morfología del río también puede verse afectada por la interacción humana, que es una forma en que el río responde a un nuevo factor en la forma en que el río puede cambiar su curso. Un ejemplo de cambio inducido por el hombre en la morfología de los ríos es la extracción de grava del lecho del río, que altera el flujo de agua y sedimentos fluviales. Un régimen fluvial es un sistema de equilibrio dinámico, que es una forma de clasificar los ríos en diferentes categorías. También vale la pena mencionar que los planos fluviales pudieron haber tenido diferentes formas, desde canal recto hasta sinusoidal y trenzado. La ingeniería hidráulica es otro subconjunto de la gestión del ciclo del agua que se centra en estos temas.

En conclusión, estas partes han sido el foco de estudios de científicos e ingenieros del agua con el fin de ampliar nuestro conocimiento a escala global y local para mejorar nuestra capacidad de pronosticar el tiempo, el clima, analizar y gestionar los recursos hídricos, comprender la geología y los cambios morfológicos. y evaluar los impactos ambientales y la salud de los ecosistemas; Al igual que en esta tesis, el plan de investigación tenía como objetivo arrojar luz sobre algunas partes oscuras de las ciencias del agua.

1.2. Hipótesis de trabajo y principales objetivos a alcanzar

As described in the introduction, there are many problems associated with water management and water engineering that need to be researched, and this research plan will try to address some parts of them.

In general, it seems that the main problems stem from human intervention in nature. This issue can be studied and analyzed from different angles, especially holistic and macroscopic view and partial and microscopic view.

It is worth noting that human impact on the environment or anthropogenic impact on the environment includes changes to biophysical environments and to ecosystems, biodiversity, and natural resources caused directly or indirectly by humans, including global warming, environmental degradation (such as ocean acidification), mass extinction and biodiversity loss, ecological crisis, and ecological collapse. Modifying the environment to fit the needs of society is causing severe effects. Some human activities that cause damage (either directly or indirectly) to the environment on a global scale include population growth, overconsumption, overexploitation, pollution, and deforestation. Some of the problems, including global warming and biodiversity loss, have been proposed as representing catastrophic risks to the survival of the human species.

From a holistic point of view, it will naturally be the subject of research on the catchment area and sustainability of environment. This catchment would either be a very large natural catchment outside the city and the discussion would be about rainfall, flood or water resources management, or it will be a study of an urban area and focus on floods or stormwater management. In this context, two types of changes due to human intervention in natural cycles will be examined. The first type will be of direct human intervention in nature such as extensive use of surface water and groundwater resources and evaluating its effects on important surrounding infrastructures and the second type will examine the indirect effects of human intervention in nature,

such as increasing the amount and intensity of wildfires in nature due to climate change and other parameters, and evaluating its effects on the amount, intensity and changes in the characteristics of subsequent floods. In this regard, risk analysis and management will be tried as a powerful scientific tool in assessing the conditions or facilitating the development of water control and management methods.

Another very important area research regarding the increase of cities' resilience to water shortage problems and its negative impacts is the use of modern techniques. One of the problems with using such modern techniques is usually the very expensive nature changes from existing traditional systems to modern ones, as well as the need for sporadic and city-wide development. In this regard, an approach will be tried to propose a technique to create a centralized system with a very low cost to change the existing stormwater urban systems to a modern one which contribute heavily in terms of sustainability.

From a partial point of view, the effects of man-made changes on water bodies will be examined and analyzed from a hydraulic perspective. Accumulation of aggregates (gravels and sands) on river beds, creates a valuable source of materials highly important in construction and hard to ignore economically. However, large-scale extraction of these materials from riverbeds can cause severe morphological changes which might be followed by many harmful impacts. The most visible impact is bed deformation. Creation of a pit in a riverbed would lead to changes in river flow regime and imbalance in the sediment equilibrium which can cause downstream progressive bed degradation. It could also increase grade slope and instability of riverbanks. In addition, if the pit is deep enough it creates a cascading flow, the resulting erosion can turn into a backward erosion and threaten the upstream of the pit. Moreover, mining along rivers can divert streams to their banks and initiate eroding; the problems of such fluvial erosions generated by these activities can affect properties and civil works located in the vicinity of rivers and have become a severe problem. The aim of research will be to consider aspects of water flow as well as sediment and morphology in a river under gravel mining.

The Above Paragraphs In Spanish:

Como se describió en la introducción, hay muchos problemas asociados con la gestión del agua y la ingeniería hidráulica que necesitan ser investigados, y este plan de investigación intentará abordar algunas partes de ellos.

En general, parece que los principales problemas derivan de la intervención humana en la naturaleza. Este tema puede estudiarse y analizarse desde diferentes ángulos, especialmente desde una visión holística y macroscópica y desde una visión parcial y microscópica.

Vale la pena señalar que el impacto humano en el medio ambiente o el impacto antropogénico en el medio ambiente incluye cambios en los entornos biofísicos y en los ecosistemas, la biodiversidad y los recursos naturales causados directa o indirectamente por los humanos, incluido el calentamiento global, la degradación ambiental (como la acidificación de los océanos), extinción masiva y pérdida de biodiversidad, crisis ecológica y colapso ecológico. Modificar el medio ambiente para adaptarlo a las necesidades de la sociedad está provocando efectos graves. Algunas actividades humanas que causan daños (ya sea directa o indirectamente) al medio ambiente a escala global incluyen el crecimiento demográfico, el consumo excesivo, la sobreexplotación, la contaminación y la deforestación. Se ha propuesto que algunos de los problemas, incluido el calentamiento global y la pérdida de biodiversidad, representan riesgos catastróficos para la supervivencia de la especie humana.

Naturalmente, desde un punto de vista holístico, será objeto de investigaciones sobre la cuenca hidrográfica y la sostenibilidad del medio ambiente . Esta cuenca sería una cuenca natural muy grande fuera de la ciudad y la discusión sería sobre lluvias, inundaciones o gestión de recursos hídricos, o será un estudio de un área urbana y se centraría en inundaciones o gestión de aguas pluviales. En este contexto, se examinarán dos tipos de cambios debidos a la intervención humana en los ciclos naturales. El primer tipo será de intervención humana directa en la naturaleza, como el uso extensivo de recursos de aguas superficiales y subterráneas y la evaluación de sus efectos en importantes infraestructuras circundantes, y el segundo tipo examinará los efectos indirectos de la intervención humana en la naturaleza.

como aumentar la cantidad e intensidad de los incendios forestales en la naturaleza debido al cambio climático y otros parámetros, y evaluar sus efectos sobre la cantidad, intensidad y cambios en las características de inundaciones posteriores. En este sentido, se probará el análisis y la gestión de riesgos como una poderosa herramienta científica para evaluar las condiciones o facilitar el desarrollo de métodos de control y gestión del agua.

Otro área de investigación muy importante sobre el aumento de la resiliencia de las ciudades ante los problemas de escasez de agua y sus impactos negativos es el uso de técnicas modernas. Uno de los problemas del uso de técnicas tan modernas suele ser el carácter muy costoso de los cambios de los sistemas tradicionales existentes a los modernos, así como la necesidad de un desarrollo esporádico y en toda la ciudad. En este sentido, se intentará proponer una técnica para crear un sistema centralizado de muy bajo coste para cambiar los sistemas urbanos de aguas pluviales existentes por uno moderno que contribuya en gran medida en términos de sostenibilidad.

Desde un punto de vista parcial, se examinarán y analizarán desde una perspectiva hidráulica los efectos de los cambios provocados por el hombre en las masas de agua. La acumulación de áridos (gravas y arenas) en los lechos de los ríos crea una valiosa fuente de materiales de gran importancia en la construcción y difícil de ignorar económicamente. Sin embargo, la extracción a gran escala de estos materiales de los lechos de los ríos puede provocar graves cambios morfológicos a los que podrían seguir muchos impactos perjudiciales. El impacto más visible es la deformación del lecho. La creación de un pozo en el lecho de un río provocaría cambios en el régimen de flujo del río y un desequilibrio en el equilibrio de los sedimentos que puede causar una degradación progresiva del lecho río abajo. También podría aumentar la pendiente y la inestabilidad de las riberas de los ríos. Además, si el pozo es lo suficientemente profundo crea un flujo en cascada, la erosión resultante puede convertirse en una erosión hacia atrás y amenazar la corriente arriba del pozo. Además, la minería a lo largo de los ríos puede desviar arroyos hacia sus orillas e iniciar la erosión; Los problemas de este tipo de erosiones fluviales generadas por estas actividades pueden afectar propiedades y obras civiles ubicadas en las cercanías de los ríos y se han convertido en un grave problema. El objetivo de la investigación será considerar aspectos del flujo de agua, así como los sedimentos y la morfología en un río sometido a extracción de grava.

1.3. Metodología

From the partial-specific point of view, one of the most problematic man-made changes on rivers is extracting gravel and sediment from riverbeds. In this thesis, an attempt has been made to address one of these lesser-known aspects; maximum scour depth as one of the most important problems of gravel mining pits.

In this regard, experimental data are crucial to build the model and its calibration. Due to the type of study that different models should be created with comparability. Then, based on the physical model, an accurate computer model is created and calibrated using computer models. Afterwards, different models are constructed and simulated to understand different aspects of the phenomenon. The results of these simulations are then extracted and set together for comparison. Finally, an attempt is made to identify the trend of changes and the reasons behind this process.

It is worth noting that the use of proper computer models that can handle the complexity of such phenomena is really important. Therefore, CCHE2D was selected to be the computer model. CCHE2D is a general model for two-dimensional simulation and analysis of river flows, dam break flows, non-uniform sediment transport, morphologic processes, coastal processes, pollutant transport and water quality. These processes are solved with the depth integrated Reynolds equations, mass transport equations, sediment sorting equation, bed load and bed deformation equations. This model is based on Efficient Element Method, a collocation approach of the Weighted Residual Method. The numerical scheme can handle subcritical, supercritical flows and their transition. In order to examine its precision in simulating another more complex 3D software will be used to compare the results. Flow3D (Flow Science, Inc., 2007) is a CFD software that employs numerical techniques to solve the fluid motion equations to obtain transient, three-dimensional solutions to multi-scale, multi-physics flow problems in which Computational Fluid Dynamics (CFD) methods are always used for the simulation of flow process by discretization and solving of Navier-Stokes and continuity equations for the computational cells. An array of physical and numerical options allows users to apply Flow3D to a wide variety of fluid flows and heat transfer phenomena.

From a holistic point of view, various issues are examined. One of these issues is the effects of man-made changes at the basin level, such as the effects of climate change and its impacts on the rainfall pattern and how to better understand the rainfall patterns. In this regard an innovative framework is established to give the opportunity to have a practical approach of categorizing rainfall patterns through cluster analysis.

Another aspect will be in the development of stormwater management network of urban basins, where it has its importance as the protection structure against floods and runoffs, it could have the functionality of an important element in improving water balance in cities and bring more sustainable environment. An innovative approach is designed in order to change the functionality of the mentioned network to have both functionality at the same time; mostly through aquifer water recharge.

This approach could be a very effective way to protect coastal cities against saline water intrusion. Groundwater extraction is the primary cause of saltwater intrusion. Groundwater is the main source of drinking water in many coastal areas of the world, and extraction has increased over time. Under baseline conditions, the inland extent of saltwater is limited by higher pressure exerted by the freshwater column, owing to its higher elevation. Groundwater extraction can lower the level of the freshwater table, reducing the pressure exerted by the freshwater column and allowing the denser saltwater to move inland laterally. By recharging the aquifer using excess runoff from stormwater, groundwater level would rise as well as its pressure and therefore it would drive the saline water back.

The Above Paragraphs In Spanish:

Desde el punto de vista parcial-específico, uno de los cambios más problemáticos provocados por el hombre en los ríos es la extracción de grava y sedimentos de los lechos de los ríos. En esta tesis se ha intentado abordar uno de estos aspectos menos conocidos; La profundidad máxima de socavación es uno de los problemas más importantes de los pozos de grava.

En este sentido, los datos experimentales son cruciales para construir el modelo y su calibración. Debido al tipo de estudio se deben crear diferentes modelos con comparabilidad. Luego, basándose en el modelo físico, se crea y calibra un modelo informático preciso utilizando modelos informáticos. Posteriormente, se construyen y simulan diferentes modelos para comprender diferentes aspectos del fenómeno. Luego, los resultados de estas simulaciones se extraen y se reúnen para compararlos. Finalmente, se intenta identificar la tendencia de los cambios y las razones detrás de este proceso.

Vale la pena señalar que el uso de modelos informáticos adecuados que puedan manejar la complejidad de tales fenómenos es realmente importante . Por lo tanto, se seleccionó CCHE2D como modelo de computadora. CCHE2D es un modelo general para simulación bidimensional y análisis de caudales de ríos, flujos de rotura de presas, transporte de sedimentos no uniforme, procesos morfológicos, procesos costeros, transporte de contaminantes y calidad del agua. Estos procesos se resuelven con las ecuaciones de Reynolds integradas en profundidad, ecuaciones de transporte de masa, ecuaciones de clasificación de sedimentos, ecuaciones de carga del lecho y ecuaciones de deformación del lecho. Este modelo se basa en el método de elementos eficientes , un enfoque de colocación del método residual ponderado. El esquema numérico puede manejar flujos subcríticos, supercríticos y su transición. Para examinar su precisión en la simulación se utilizará otro software 3D más complejo para comparar los resultados. Flow3D (Flow Science, Inc., 2007) es un software CFD que emplea técnicas numéricas para resolver las ecuaciones de movimiento de fluidos para obtener soluciones tridimensionales transitorias a problemas de flujo multiescala y multifísicos en los que se utiliza la dinámica de fluidos computacional (CFD). Siempre se utilizan métodos para la simulación del proceso de flujo mediante discretización y resolución de Navier-Stokes y ecuaciones de continuidad para las celdas computacionales. Una variedad de opciones físicas y numéricas permite a los usuarios aplicar Flow3D a una amplia variedad de flujos de fluidos y fenómenos de transferencia de calor.

Desde un punto de vista holístico, se examinan diversas cuestiones. Una de estas cuestiones son los efectos de los cambios provocados por el hombre a nivel de cuenca, como los efectos del cambio climático y sus impactos en el patrón de precipitaciones y cómo comprender mejor los patrones de lluvia. En este sentido, se establece un marco innovador para brindar la oportunidad de tener un enfoque práctico para categorizar los patrones de lluvia a través del análisis de conglomerados.

Otro aspecto será el desarrollo de la red de gestión de aguas pluviales de las cuencas urbanas, donde tiene su importancia como estructura de protección contra inundaciones y escorrentías, podría tener la funcionalidad de un elemento importante para mejorar el equilibrio hídrico en las ciudades y lograr un medio ambiente más sostenible . Se diseña un enfoque innovador con el fin de cambiar la funcionalidad de la red mencionada para tener ambas funcionalidades al mismo tiempo; principalmente a través de la recarga de agua de los acuíferos.

Este enfoque podría ser una forma muy eficaz de proteger las ciudades costeras contra la intrusión de agua salina. La extracción de agua subterránea es la causa principal de la intrusión de agua salada. El agua subterránea es la principal fuente de agua potable en muchas zonas costeras del mundo y su extracción ha aumentado con el tiempo. En condiciones de referencia, la extensión tierra adentro del agua salada está limitada por la mayor presión ejercida por la columna de agua dulce, debido a su mayor elevación. La extracción de agua subterránea puede reducir el nivel del nivel freático, reduciendo la presión ejercida por la columna de agua dulce y permitiendo que el agua salada, más densa, se mueva tierra adentro lateralmente. Al recargar el acuífero utilizando el exceso de escorrentía de las aguas pluviales, el nivel del agua subterránea aumentaría así como su presión y, por lo tanto, haría retroceder el agua salina.

Capítulo 2 "ARTÍCULO 1"

2.1. Objetivo

Accumulation of aggregates (gravels and sands) on river beds, creates a valuable source of materials highly important in construction and hard to ignore economically. However, large-scale extraction of these materials from riverbeds can cause severe morphological changes which might be followed by many harmful impacts.

The most visible impact is bed deformation. Creation of a pit in a riverbed would lead to changes in river flow regime and imbalance in the sediment equilibrium which can cause downstream progressive bed degradation. It could also increase grade slope and instability of riverbanks. In addition, if the pit is deep enough it creates a cascading flow, the resulting erosion can turn into a backward erosion and threaten the upstream of the pit.

With the development of computers and their increasing computing power, several numerical methods were developed; however, due to the complexity of the subject, many of its aspects remain unknown. In the present study, an attempt has been made to address one of these lesser-known aspects; maximum scour depth as one of the most important problems of gravel mining pits in the interaction with the river curvature.

The Above Paragraphs In Spanish:

La acumulación de áridos (gravas y arenas) en los lechos de los ríos crea una valiosa fuente de materiales de gran importancia en la construcción y difícil de ignorar económicamente. Sin embargo, la extracción a gran escala de estos materiales de los lechos de los ríos puede provocar graves cambios morfológicos a los que podrían seguir muchos impactos perjudiciales.

El impacto más visible es la deformación del lecho. La creación de un pozo en el lecho de un río provocaría cambios en el régimen de flujo del río y un desequilibrio en el equilibrio de los sedimentos que puede causar una degradación progresiva del lecho río abajo. También podría aumentar la pendiente y la inestabilidad de las riberas de los ríos. Además, si el pozo es lo suficientemente profundo crea un flujo en cascada, la erosión resultante puede convertirse en una erosión hacia atrás y amenazar la corriente arriba del pozo.

Con el desarrollo de las computadoras y su creciente potencia informática, se desarrollaron varios métodos numéricos; sin embargo, debido a la complejidad del tema, muchos de sus aspectos aún se desconocen. En el presente estudio se ha intentado abordar uno de estos aspectos menos conocidos; La profundidad máxima de socavación como uno de los problemas más importantes de los graveros en la interacción con la curvatura del río.

2.2. Metodología:

In this regard, experimental data are crucial to build the model and its calibration. Due to the type of study that different models should be created with comparability, it is impractical to use field data because of natural complexities of rivers and external influencing factors; thus, the most appropriate data for such a study is laboratory data. Respectively, the best study that has been done and its data has been published is the studies of Lee et al. as described above.

Therefore, based on the physical model made in the studies of Lee et al., an accurate computer model was created and calibrated using CCHE2D. Afterwards, without any changes in any other parameter, different models were constructed and simulated just by changing the amount of the curvature. The results of these simulations were then extracted and put together for comparison. Finally, an attempt was made to identify the trend of changes and the reasons behind this process.

The Above Paragraphs In Spanish:

En este sentido, los datos experimentales son cruciales para construir el modelo y su calibración. Debido al tipo de estudio en el que se deben crear diferentes modelos con comparabilidad, no es práctico utilizar datos de campo debido a las complejidades naturales de los ríos y los factores de influencia externos; por tanto, los datos más apropiados para dicho estudio son los datos de laboratorio. Respectivamente, el mejor estudio que se ha realizado y sus datos se han publicado son los estudios de Lee et al. como se describió anteriormente.

Por lo tanto, basándose en el modelo físico realizado en los estudios de Lee et al., se creó y calibró un modelo informático preciso utilizando CCHE2D. Posteriormente, sin cambios en ningún otro parámetro, se construyeron y simularon diferentes modelos simplemente cambiando la cantidad de curvatura. Luego, los resultados de estas simulaciones se extrajeron y se reunieron para compararlos. Finalmente, se intentó identificar la tendencia de los cambios y las razones detrás de este proceso.

2.3. resultados:

As can be seen from the results, the maximum scour depth is almost always increased. However, it is clear that a curved channel without a pit will also have more degradation than a straight channel and that is due to the increase in velocity at the outer wall of the bend; therefore, the effect of the mining pit is isolated and investigated separately. For this purpose, a parameter called Δ was defined which was considered equal to the maximum scour depth with the gravel mining pit minus the maximum scour depth without it.

Changes in Δ as the net effect of mining pit in maximum scour depth could be described in three parts; a reducing wing, an extremum and an increasing wing. Increasing the curvature, the value of Δ, from direct channel to channel with light curvature of C/L=2.38 is decreased. At this point, Δ is eventually close to zero which in another word means that there are no difference in maximum scour depth between a channel with a pit and a channel without a pit at this curvature degree. Afterwards, the increasing wing of Δ-C/L diagram is formed.

The Above Paragraphs In Spanish:

Como puede verse en los resultados, la profundidad máxima de socavación casi siempre aumenta. Sin embargo, está claro que un canal curvo sin foso también tendrá mayor degradación que un canal recto y eso se debe al aumento de velocidad en la pared exterior de la curva; por lo tanto, el efecto del tajo minero se aísla e investiga por separado. Para ello se definió un parámetro denominado Δ el cual se consideró igual a la profundidad máxima de socavación con el tajo de grava menos la profundidad máxima de socavación sin él.

Los cambios en Δ como efecto neto del tajo minero en la profundidad máxima de socavación podrían describirse en tres partes; un ala reductora, un extremo y un ala creciente. Al aumentar la curvatura, se disminuye el valor de Δ, de canal directo a canal con curvatura de luz de C/L=2,38. En este punto, Δ eventualmente se acerca a cero, lo que en otras palabras significa que no hay diferencia en la profundidad máxima de socavación entre un canal con picadura y un canal sin picadura en este grado de curvatura. Posteriormente, se forma el ala creciente del diagrama Δ-C/L.

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Interaction between gravel mining pits and river curvature on maximum scour depth through 2D hydraulic modelling

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ABSTRACT

To investigate the interacting effects of rivers curvature and gravel mining pits on rivers morphology, channels with different curvatures were analyzed using a 2D-3D modelling approach implemented through the code CCHE2D. A parameter (Δ: the maximum channel scour depth with existence of pit minus the maximum scour depth without pit) was defined as the net effect of gravel mining pits. The results indicated that the net effect of a pit on the maximum scour depth, from a straight channel to a channel with the curvature (C/L) of 2.38, decreases, and then, increases with higher degrees of curvature. The study of influential parameters showed that the cause of this event is due to the simultaneous effects of two opposing phenomena; while one (smoothing) reduces the Δ, the other (secondary flow) increases it. The reducing effect (smoothing) stems from the asymmetry of the flow velocity in the channel bend. This causes bed deformation in a way that channel experience a gradual decrease in velocity and as a result, less sediment loss. Furthermore, the boosting effect goes back to the existence of secondary flow in the bends, which grows stronger as the amount of curvature increases.

1. Introduction

Accumulation of aggregates (gravels and sands) on river beds, creates a valuable source of materials highly important in construction and hard to ignore economically. However, large-scale extraction of these materials from riverbeds can cause severe morphological changes which might followed by many harmful impacts. The most visible impact is bed deformation.

Creation of a pit in a riverbed would lead to changes in river flow regime and imbalance in the sediment equilibrium which can cause downstream progressive bed degradation. It could also increase grade slope and instability of riverbanks (Luo et al., 2007). In addition, if the pit is deep enough it creates a cascading flow, the resulting erosion can turn into a backward erosion and threaten the upstream of the pit. Moreover, mining along rivers can divert streams to their banks and initiate eroding; the problems of such fluvial erosions generated by these activities can affect properties and civil works located in the vicinity of rivers and have become a severe problem (Stover and Montgomery, 2001). In some cases, degradation of the river channel can affect even the stability of bridges as in Helleh River it caused up to 1.27 m at the bridge foundation (Zolghadr et al., 2021). A variety of examples of such adverse effects of gravel mining are presented in Raynov et al. (1986). Depending on the type of river and how construction materials are extracted, braided rivers could be another consequence of the existence of gravel mining pits. Furthermore, gravel extraction leads to the suspension of sediments in the stream, which will have severe negative effects on the aquatic life and environment of the rivers (Asaeda and Sanjaya, 2017). Overall, gravel mining could have dramatic effects on all aspects of rivers. The most important of these effects are morphological changes as the consequences can be seen kilometers downstream and upstream of the extraction site (Calle et al., 2017; Arróspide et al., 2018; Costea, 2018). Studying some cases even show that between 23 and 47 years after the end of mining, the side effects have still not yet fully recovered (Dépret et al., 2021;Picco et al., 2017).

The impact of human activities on river systems has reached a state in which they can no longer be considered to be controlled only by natural processes of the Earth but also by anthropogenic forces in many regions of world (Zhao et al., 2020). The first way to deal with gravel mining problem in rivers is to forbid any extraction from the riverbeds, the consequences of such decision would be to ignore such valuable source of materials. The second method deals with it by understanding the changes and their magnitude, and thus, help decision makers

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minimizing the problems.

In this study, the most important effect, the riverbed degradation, will be discussed. To understand this phenomenon, several approaches have been developed over the years which could be classified in three general categories. The first category includes empirical formulas describing the deformation of river bed level in a cross section through time. The outcome of this method is generally exponential functions or formulas of decay. The coefficients in these formulas should be calibrated with observed bed level (Simon, 1989; Simon and Darby, 2002; Simon and Rinaldi, 2006; Rascher et al., 2018). The second category consists of models based on Analysis of sediment budget in river reaches. This approach integrates sediment transport processes in time and space and converts them into a single number as total quantity of river bed degradation (Collins and Dunne, 1989; Knuuti and McComas, 2003; Zhai et al., 2020). However, it is worth mentioning that sediment transport for streams is exceedingly variable because sediment transport is a power function of stream flow, which varies significantly from year to year, and depends on sediment supply which is difficult to characterize. Thus, an annual average sediment load might be meaningless (Kondolf and Swanson, 1993). The third category includes Mathematical models based on the solution of equations of water and sediment transport. Mathematical-physical based approaches consider gravel mining in river beds as digging a pit in the bed and using experimental, analytical and numerical techniques to predict movement and deformation of the pit through river bed within the context of time and place (Lee et al., 1993; Gill, 1994; Boillat et al., 2006; Teo et al., 2017; Yao et al., 2019).

Few research in mathematical analysis and experimental study of the gravel mining have been done and the most important ones can be noted as follows. Ahmadi (1990) worked out the problem using a one-dimensional model. The results shows that the allowable mining amount is a maximum of about one-third or a quarter of the annual bed load, and the excess will cause erosion and degradation of the river bed and water level upstream and downstream to a considerable and undesirable extent. In a very important study, Lee, Fu & Songe composed many laboratory tests of rectangular pits using uniform deposition of material and proposed a formula to predict the changes in channel after extraction of material (Lee et al., 1993). The purpose of this study was to investigate temporal and spatial variations of rectangular pits under the actions of different flow conditions. A flume with a length of 17 m and a width of 0.6 m was used with uniform deposition of sand with an average diameter of 1.4 mm to investigate in-stream sand- and gravel-mining operations. Five different pit geometries and 10 different flow conditions were chosen to perform the experiments. Based on the experimental results, a systematic procedure with empirical formulas for prediction of the shape and migration of the pits was proposed. The model was verified by the experimental data with satisfactory agreements. The results showed that the maximum depth of scour decreases with increasing carrying capacity and the effective length of erosion is inversely related to carrying capacity. The movement of the harvest pond can be divided into two time periods: a convection period and a diffusion period. The velocity of pit migration is constant in each period and increases with increasing carrying capacity and effective length and is inversely related to the depth of the pit. The correlation equation between the maximum scour depth and the effective length of erosion with the shape and velocity of pits has been obtained in these studies. These equations were then used to predict the size, shape, and migration velocity of rectangular pits. Gill (1994) offered an approximate theoretical solution of gravel mining pits with any regular geometric shape dug in an erosive riverbed based on the works of Lee et al. (1993). Recently, research in the field of numerical simulation using computer models have been done, among them works of Chen et al. (2008), Chen and Liu (2009) and Chen et al. (2010) can be mentioned. With the development of computers and their increasing computing power, several numerical methods were developed; however, due to the complexity of the subject, many of its aspects remain unknown. In the present study, an attempt has been made to address one of these lesser-known aspects; maximum scour depth as one of the most important problems of gravel mining pits in the interaction with the river curvature. In this regard, experimental data are crucial to build the model and its calibration. Due to the type of study that different models should be created with comparability, it is impractical to use field data because of natural complexities of rivers and external influencing factors; thus the most appropriate data for such a study is laboratory data. Respectively, the best study that has been done and its data has been published is the studies of Lee et al. as described above. Therefore, based on the physical model made in the studies of Lee et al., an accurate computer model was created and calibrated using CCHE2D. Afterwards, without any changes in any other parameter, different models were constructed and simulated just by changing the amount of the curvature. The results of these simulations were then extracted and put together for comparison. Finally, an attempt was made to identify the trend of changes and the reasons behind this process.

This paper is aimed to investigate the interacting effects of rivers curvature and gravel mining pits on rivers morphology, channels with different curvatures using a 2D-3D modelling approach implemented through the code CCHE2D.

2. Materials and methods

2.1. CCHE2D model

CCHE2D is a general model for two-dimensional simulation and analysis of river flows, dam break flows, non-uniform sediment transport, morphologic processes, coastal processes, pollutant transport and water quality. These processes are solved with the depth integrated Reynolds equations, mass transport equations, sediment sorting equation, bed load and bed deformation equations. This model is based on Efficient Element Method, a collocation approach of the Weighted Residual Method. The numerical scheme can handle subcritical, supercritical flows and their transition (Jia and Sam, 2001).

Suspended load transport occurs mostly at a non-equilibrium state and is usually simulated by non-equilibrium transport models. However, most of the existing sediment transport models adopt the assumption of local equilibrium when simulating bed load transport. Recent studies on the spatial and temporal lags of bed load transport show that the non-equilibrium transport model for bed load is needed in many cases, such as strong erosion and strong deposition, especially under unsteady flow conditions. The CCHE2D model implements a full non-equilibrium transport model for bed-material load (bed load plus suspended load). Three different non-equilibrium approaches are proposed to handle the cases where sediment transport occurs mainly as bed load, mainly as suspended load, or as full total load, respectively (Jia and Sam, 2001).

In addition, the CCHE2D model can simulate the transport of non-uniform sediment mixtures with multiple size classes, which is common in natural rivers and streams. Several formulas for fractional non-cohesive sediment transport capacity and movable bed roughness are provided so that the user can choose the most appropriate one for the specific case under study. Another significant improvement of the CCHE2D sediment transport model is the capability of simulating cohesive sediment transport. Two approaches are adopted for the transport of sediment with weak and strong cohesive properties (Jia and Sam, 2001).

In 2009, Deng Chen et al. compared the results of the one-dimensional model HEC-RAS and CCHE2D on the Salt River; although the results were very similar, they differed in a few cases, and the CCHE2D model showed considerable superiority. HEC-RAS showed that an incision occurs above the pits, while CCHE2D suggested that downstream erosion would be more significant. HEC-RAS predicted a maximum bed reduction of 3.6 m for pit-1 and a distance of 2.9 m upstream of pit-2, while CCHE2D predicted a maximum reduction of bed level of 3.3 m. In addition, CCHE2D showed that most of the sediment deposition occurs at the upstream end of the pits and the maximum sediment accumulation was 1.7 m for pit-1 and 1.9 for pit-2. Based on field observations and previous modeling studies, the two-dimensional model had more accurate and realistic results in flood cover, heterogeneous sediment investigation and channel morphological changes (Chen et al., 2009).

2.2. Calibration of CCHE2D model

To perform analysis, Lee et al. laboratory flume as described previously was constructed using CCHE MESH. The result is shown in Fig. 1.

This model is a quadrilateral mesh with grid size of 0.02 m; therefore, the model is divided into 850 × 30 sections. A pit with a depth of 0.06 m and 0.76 m in length was built at the distance of 9.5 m from the beginning of the channel. Based on the experimental data initial conditions was set as flow discharge equal to 0.043 cms (m3.s-1), primary water level equal to 0.117 m and no sediment was supplied from upstream. The bedmaterial was uniform sand with a median particle size, d50, of 1.4 mm.

Based on lee et al.'s (1993) work, the deformation and migration of an in-stream mining pit can be divided into two periods. The first period is from the beginning of deformation to the moment when the upstream boundary of the mining pit reaches the original downstream end of the pit; the second period starts from that moment onward. The first period is dominated by the convection process, during which the maximum scour depth remains more or less constant, spatially and temporally; and the second period is dominated by the diffusion process and the maximum scour depth starts to decrease as time proceeds. Therefore, in order to compare the maximum scour depth, convection period is used and considered to be 2 h based on the experimental results.

Chen et al. (2010) examined the non-equilibrium adaptation parameters of a depth-averaged two-dimensional hydrodynamic and sediment transport model through comparison with measured data of Lee et al. (1993) Experiments on mining-pit migration. Simulation time step of 10 s and the grid size of 0.02 m were considered to be appropriate. In this study, based on the sensitivity analysis of the research mentioned, grid size is chosen to be 0.02 m and the non-equilibrium adaptation parameter of 0.02 m is used (Chen et al., 2010).

The mixing length turbulence model was used to calculate the flow turbulence and the Van Rinn formula (b1984) was used to calculate the bed roughness (Jia and Sam, 2001).

Among several formulas for calculating non-cohesive sediment transport that have been published in recent decades, four formulas have been selected by reviewing and evaluating extensive research in this field, computational capabilities and experiments with abundant laboratory and field data for use in the CCHE2D model. These formulas include the modified Ackers and White (1983), the SEDTRA module (1995) presented by Garbrecht and Kuhnle, and also the formula of Wu, Wang and Jia (2000) and the formula of Englund and Hans (1967), (Jia and Sam, 2001).

These formulas along with Karim (1998) and Zhang modified formulas (1992) were tested in the technical guide of CCHE2D software with Brownley data for homogeneous bed and bed load and toffaletti data for inhomogeneous bed. The results testify to the superiority of Wu et al. Formula in the vast majority of experiments, so it is chosen as the method of calculating sediment transport (Jia and Sam, 2001).

The minimum dry water depth is considered to be 2 mm, which never occurred during the whole simulation process. Even assuming a minimum depth of 2 cm, it did not occur.

Flow3D (Flow Science, Inc., 2007) is a CFD software that employs numerical techniques to solve the fluid motion equations to obtain transient, three dimensional solutions to multi-scale, multi-physics flow problems in which Computational Fluid Dynamics (CFD) methods are always used for the simulation of flow process by discretization and solving of Navier-Stokes and continuity equations for the computational cells. An array of physical and numerical options allows users to apply Flow3D to a wide variety of fluid flows and heat transfer phenomena (Ghasemi and Soltani-Gerdefaramarzi, 2017).

For better comparison, different models of experiments were constructed by Flow3D software and calibrated with laboratory data. The best results were obtained with Peter-Meyer sediment equation, RNG turbulence equation and 2 cm mesh size.

As shown in Fig. 2, bed deformation and displacement of the maximum scour depth by CCHE2D model is compared to experimental data and Flow3D results. At first glance, three cases are clearly recognizable. First, bed changes upstream of the pit, including pre-pit bed elevation and upstream wall slope, are well consistent with experimental data. In this regard, the most important point mentioned in Lee et al.'s study is the 12-degree angle of the upstream wall, where the model was good at simulating, and even the results are slightly better than Flow3D model results. The simulation is well matched with experimental data except for the height of the upstream edge, which is calculated more than experimental data, although this is of little importance as this study deals with the maximum scour depth. Second, the position and depth of scouring are calculated slightly better than Flow3d model. And finally, the downstream wall of the hole is reasonably estimated, although like the Flow3D model, with some error. In the following, goodness-to-fit of simulation results is compared with

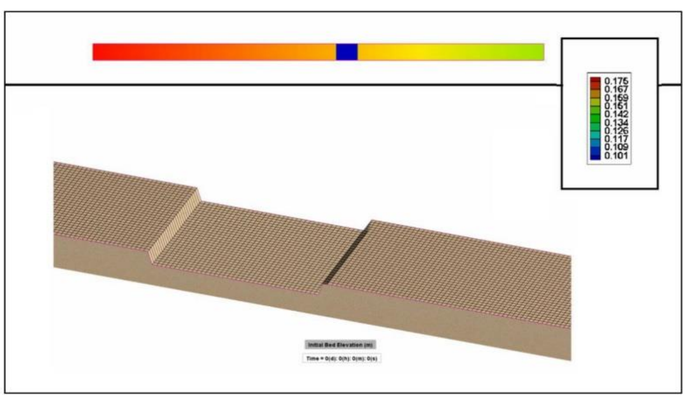


Fig. 1. View of the generated mesh based on Lee et al. 1993 model using CCHE MESH.

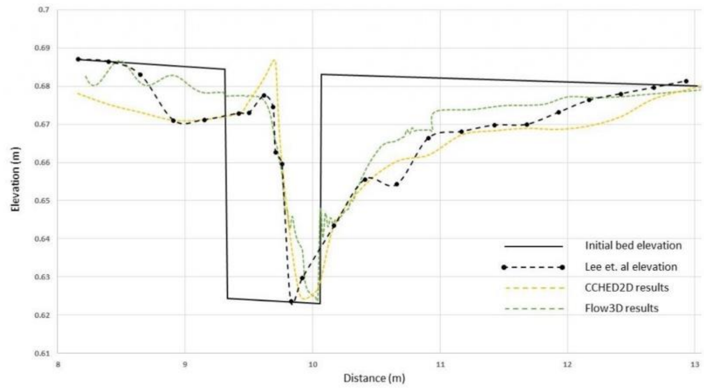


Fig. 2. Comparison of simulated results of CCHE2D and Flow3D vs lee et al. observed bed profile.

experimental data by different parameters.

The goodness-of-fit between computed and measured bed elevations were evaluated by three statistical parameters including the bias, the average geometric deviation (AGD), and the root mean square (RMS). Each parameter provides a measure of the goodness-of-fit between the computed and measured bed elevations from a slightly different perspective. They are described as follows.

2.2.1. Bias

$$bias = \sum_{j=1}^{J}(Z_{cj} - Z_{mj})/J \quad (1)$$

where Z_c and Z_m = computed and measured bed elevations, respectively, and j = data set number. The bias with a unit of centimeter in the study represents the arithmetic mean of the difference between computed and experimental bed elevations. A positive value of bias is produced when the calculated bed elevations are generally higher than the observed conditions.

2.2.2. Agd

$$AGD = \left(\prod_{j=1}^{J} RR_j\right)^{\frac{1}{J}}$$

$$RR_j = \begin{cases} \dfrac{Z_{mj}}{Z_{cj}}, & Z_{cj} < Z_{mj} \\ \dfrac{Z_{cj}}{Z_{mj}}, & Z_{cj} \geqslant Z_{mj} \end{cases} \quad (2)$$

The dimensionless parameter AGD represents the geometrical mean of the special discrepancy ratio, RR_j.

2.2.3. Rms

$$RMS = \left(\sum_{j=1}^{J}(Z_{cj} - Z_{mj})^2/J\right)^{0.5} \quad (3)$$

The root mean square represents the quadratic mean of the difference between the computed bed elevations and the measured values. RMS is especially useful when deviations are both positive and negative such as overestimation and underestimation of bed deformation in the current calculation. RMS has a unit of centimeter in this study. These three statistical parameters bias, AGD, and RMS provide a comprehensive evaluation of the goodness-of-fit between the computed and measured bed elevation.

As can be seen from the comparison results of these parameters in Table 1, the accuracy of CCHE2D model in simulation is close to the Flow3D results and in some cases it is even better. In general, it can be concluded that the CCHE2D model has been properly and accurately simulated bed changes.

2.3. Construction of new models

In order to compare the effect of curvature on gravel mining pits, different models with different curvature had to be constructed. So, Lee et al. (1993) flume was modeled with different curvature. All the model parameters such as length, width, slope, soil type, gravel mining pit dimensions, flow and etc. remained unchanged in the new model and the only difference in the new models was the channel curvature.

As a criterion for the degree of curvature, parameter *C/L* was chosen that is a suitable indicator of the degree of curvature (Sinuosity) within which C is the arc length and L is the horizontal distance between the beginning and the end of the arc. The higher the *C/L* the sharper the curve and with *C/L* equals to 1, the channel could be direct as of Lee et al. model. In addition, another parameter called curvature (W/R), defined as dividing the channel width (W) by the radius of the arc (R) is considered alongside Sinuosity to complete the understanding of the situation.

For this purpose, using AutoCAD software, a plan of each model with C = 17 m and desired L was created, then by entering it in CCHE MESH, height values were added to it to create the slope and pit. In this research 6 new models with different *C/L* were constructed and were analyzed (Table 2).

All the selected parameters and methods mentioned in the modeling section of Lee et al. (Hereinafter referred to as the direct model) are also applied to the new models. The only item added to the new simulations is the placement of the curvature effect (Fig. 3).

Table 1
Comparison of Goodness-of-fit for Computed and Measured Results of Lee et al. (1993).

Model	CCHE2D	Flow3D
Minimum Difference (cm)	0.105	0.12
Maximum Difference (cm)	2.4	2.22
Bias (cm)	0.052	0.28
AGD	1.006	1.007
RMS (cm)	0.7	0.67
Number of points	25	25

Table 2
Models generated with different curvatures.

Model Number	1	2	3	4	5	6	7
C/L	1.00	1.09	1.47	1.89	2.38	3.00	3.28
W/L	0.00	0.06	0.20	0.44	0.50	0.67	0.75

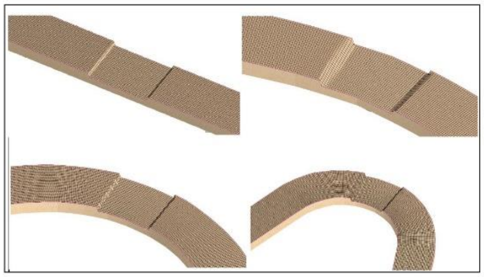


Fig. 3. Constructed models with different curvatures.

3. Results

3.1. Results from simulations

CCHE2D result files include many two-dimensional parameters, and many aspects of a hydraulic event could be analyzed to a great extent such as velocity, shear stress and eddy viscosity. It is worth noting that since the CCHE2D as a depth integrated model has no knowledge of the secondary flow, an experimental or semi-analytical approximation of the secondary flow is included in the software to predict the bed load movement in curved channels. The most influential parameter with this regard is the angle between the direction of the main flow and the shear stress near the bed. In the current model, it is approximated by the Englund (1974) relation.

$$\tan\sigma = 7\frac{h}{r} \tag{4}$$

where h is flow depth and r is the radius of curvature of the longitudinal line of the grid. The formula error is 3% according to Englund (1974). Gravity forces the moving particle to move downward in the direction of the transverse slope. In a curved channel the secondary flow tends to move against the transverse slope. When the two effects neutralize each other, equilibrium is established and the sediment particles begin to move in the main direction of the flow, which is in the longitudinal direction. Altogether, giving an average width of 0.6 (value taken from Lee et al. 1993) and the secondary flow effect will be considered in the simulation.

Another point is that although in the straight model (symmetric shape), the middle longitudinal line can be selected as a representative of the bed deformation, in the curved models, since the changes are three-dimensional and asymmetric, such a profile would only display one section and direction; thus, the profile would not represent all the changes with regard to channel bed. To solve this problem, longitudinal lines were selected from the beginning, middle and end of the channel width respectively, to display the general status of the deformation profile. Simulation Results of the model number 2 with $C/L = 1.09$ are presented in Fig. 4, Fig. 5 and Fig. 6.

The first step in understanding such complex processes is to classify the results. To begin with, as deformation of the bed is the most important parameter to be discussed considering the purpose of this research, a qualitative comparison of bed deformation could be explanatory which is described as follows.

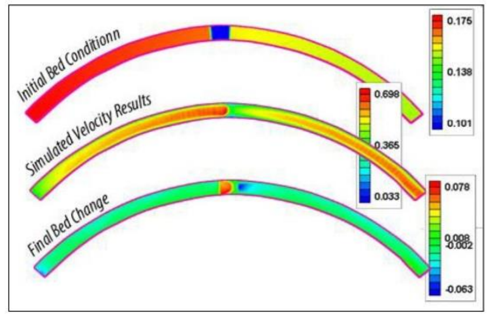


Fig. 4. Simulated results of the model with $C/L = 1.09$ after 2 hrs.

Chief among the effects of morphological parameters, the maximum scour depth could be pointed out as mining pits most destructive impact on their surrounding area; therefore, this parameter is chosen to be a representative of channels bed deformations.

From the straight channel to channel with high curvature, the maximum scour depth position moves from the center of the channel to the outer wall while sedimentation occurs close to the inner wall. Moreover, as can be seen from the results, the maximum scour depth always increases from the straight channel to the channel with high curvature. Considering that this will happen regardless of existing of a pit, the observed trend should be re-evaluated; as increase in velocity at outer wall of the bend would lead to outer wall bed degradation and sediment deposition at the inner wall vice versa.

According to the mentioned problem, the cases with and without pit effect are separately considered. In order to separate the pit effect, a parameter Δ was defined as the maximum scour depth with existence of the pit minus the maximum scour depth without existence of the pit; thus, the net effect of pit could be studied.

To build new models without pits, the elevations of pits in the previous models were eliminated. The Fig. 7 is an example of these models before and after the changes.

To obtain values of Δ, the modified models were simulated for the same 2 h. The results are shown in the Table 3 and Fig. 8.

Notable in the Table 3 and Fig. 8, there are two wings of decreasing and increasing Δ and a minimum at the $C/L = 2.38$. The following formula can be fitted to the results with the correlation factor of 0.91:

$$\Delta = -33.69\left(\frac{C}{L}\right)^2 + 158.9\left(\frac{C}{L}\right) - 190.09 \tag{5}$$

To explain this diagram (Fig. 8), it can be argued that in the cases of direct channel to the channel with light curve, the net effect of channel (Δ) reduced such that for channel with C/*L about* 2.38 this effect reduces to almost zero. This means that there seems to be no pit effect on the maximum scour depth in channel with $C/L = 2.38$. After this point, with increase in C/L, Δ increases.

3.2. Analysis of results

To understand why with sharper bends up to C/L = 2.38 the pit net effect on maximum scour depth gradually decreases and beyond this value gradually increases, all important influential parameters are determined and classified.

The only difference between these models is the magnitude of the curvature. So, the models based o the curvature degree were classified into 3 categories (Table 4).

When water flows over a mining pit, flow separation occurs and eddy rollers are developed, causing receding erosion. Meanwhile, sediment brought from upstream is trapped in the pit and causes migration of the

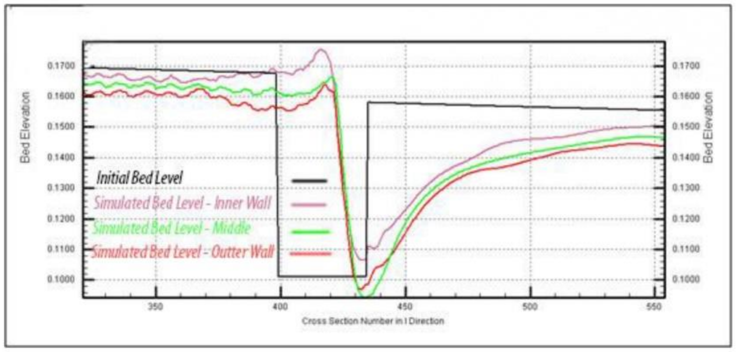


Fig. 5. Simulated results of bed deformation of the model with $C/L = 1.47$ of before and after 2 hrs.

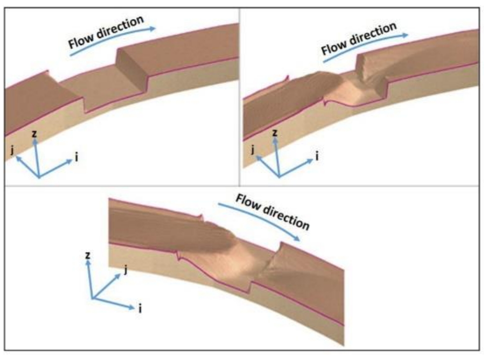


Fig. 6. Simulated results of bed profile of the model with $C/L = 1.09$ after 2 hrs.

upstream end. At the downstream end of the pit, the dividing streamline veers away from the channel bed and another separation zone is formed. At the region close to the downstream separation zone, flow accelerates, due to the sudden contraction of the channel cross-sectional area, causing local erosion. Thus, the pit starts to migrate and deform (Lee et al., 1993).

In curved channels, the events that occur in the direct channel are still happening, with slightly differences back to morphology differences. These differences can be outlined as follows:

1. Asymmetry in lateral velocity due to curvature
2. Secondary flow in bends
3. More scouring at the outer wall of the bend (due to the increased velocity and the secondary flow) and more sedimentation in the inner wall of the bend (due to the reduced flow velocity and the secondary flow) and the disappearance of morphology symmetry of the bed over time (laterally)

In the Fig. 9, the loss of symmetry of the cross sections is clearly visible.

The above information can be summarized as in the Table 5.

These parameters can be used to explain the behavior of the phenomena described in the previous sections.

One of the most important influences of mining pits on flow and sediment transport is the sudden increase and decrease in the flow depth of. In the bend, however, the process is slightly different. Firstly, a sudden increase in depth is seen and everything is the same as the direct channel. Then, asymmetry of velocity and the secondary flow due to channel bend cause more scour in the outer wall and more sedimentation in the inner wall which leads to more moderate angle adjustment of pit at the upstream head, near outer wall as it portrayed in Fig. 9. Thus the flow is longitudinally adjusted and the pit is gradually deformed so the sudden decrease of depth becomes less effective and weaker. At this state, flow faces smaller velocity slowdown at the upstream of pit and slower velocity rising up at the downstream, therefore, as a result of this gradual change in velocity instead of a sudden change, the sediment loss becomes less and scour at the downstream head of pit will be less than direct channel.

Theoretically speaking, for a fluid to begin transporting sediment that is currently at rest on a surface, the boundary (or bed) shear stress (τ_b) exerted by the fluid must exceed the critical shear stress (τ_c) for the initiation of motion of grains at the bed. For a Newtonian fluid, the shear stress at a surface element parallel to a flat plate at the point y is given by:

$$\tau_{(y)} = \mu \frac{\partial u}{\partial y} \tag{6}$$

where μ is the dynamic viscosity of the flow, u is the flow velocity along the boundary and y is the height above the boundary. The higher the shear stress on the bed, the more particles start to move and separate from it, resulting in more erosion. As can be seen from the shear stress equation, the amount of shear stress is directly related to the flow velocity and therefore it can be concluded that the higher the velocity, the higher the shear stress.

To clarify further, three models for straight channels were constructed based on Lee et al.'s experiment in the Flow3D model and simulated under the same conditions. The results of these simulations are shown in Fig. 10. As can be clearly seen, the rate of flow velocity in contact with the bed, downstream the pit (where scouring happens) has been reduced from the model with the vertical wall to the model with the smoother wall; this maybe confirm the smoothing effect.

In other words, in the simulation with direct channel after 2 h, it was observed that the 90 angle between the upstream head of pit and the bed did not change much and the sudden change of the depth continued during the simulation. However, when the channel is curved, it is seen that rough angles of the upstream and downstream heads decreased gradually which made the sudden change of depth lesser. To make the discussion easier, Hereafter this phenomenon is called "smoothing".

With sharper curvature, smoothing happens faster and gets softer, thus, reductions in pit net effect on the maximum scour depth is

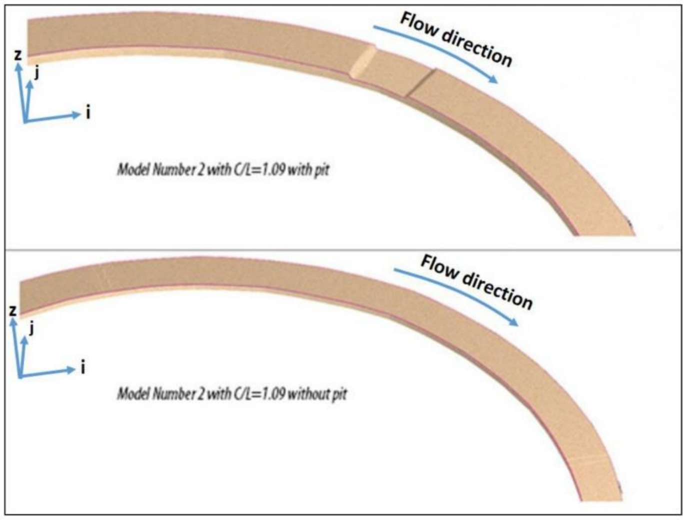


Fig. 7. Example of making models without pit.

Table 3
Results of channel maximum scour depth with pit and without pit (mm).

Δ	Maximum Scour DepthWithout the Pit (mm)	Maximum Scour DepthWith the Pit (mm)	C/L
−65	−3	−68	1
−50	−10	−60	1.09
−40	−21	−61	1.47
−10	−56	−66	1.89
−1	−74	−75	2.38
−7	−114	−121	3.00
−39	−141	−180	3.28

expected. The process proceeds to $C/L = 2.38$. At this point the net effect of pit on maximum scour depth will reduce to almost zero.

On the other hand, secondary flow gets stronger for channels with higher curvatures and creates the increasing wing of Δ-C/L diagram. Secondary flow tends to remove material from the bed and increase the scour depth in the outer wall.

Secondary flow is strongly dependent on two parameters; curvature degree and flow depth. As mentioned, with increase in the curvature degree (C/L) and thus reduction in the radius of the arc, the secondary flow becomes stronger. It is clear that creation of mining pits by removal of material increases the flow depth in the channel and this would intensifies secondary flow strength compared to channels without pits.

In fact, these two phenomena act against each other. Smoothing reduces the net effect of pits on maximum scour depth and the secondary flow increases it. The simulation results indicate that from direct channel to the channel with $C/L = 2.38$, smoothing effect is more powerful than the weak secondary flow effect (due to moderate curvature of channel bend), thus reducing the effect of mining pit on maximum scour depth happens and the reducing wing of Δ-C/L diagram

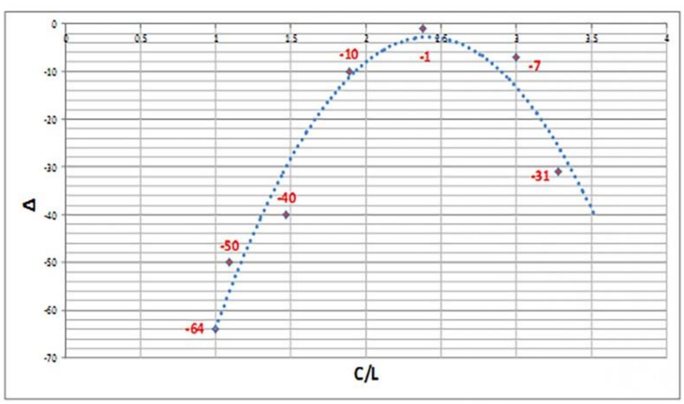
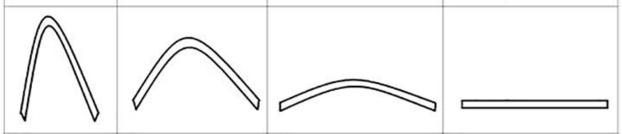


Fig. 8. Net effect of mining pit on maximum scour depth (mm).

Table 4
Categorizing channels based on their curvature values.

Second Zone	Extremum Point	First Zone	Begining Point
			
C/L >	2.38	> C/L >	1
Highly Curved Channel		Slightly Curved Channel	Straight Channel

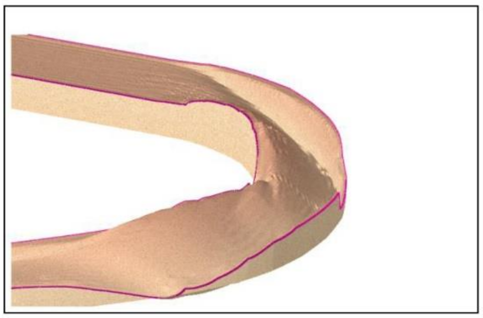


Fig. 9. Asymmetry in cross section changes in channels with curvature.

Table 5
Categorizing characteristics of each zone.

	Direct Channel	Slightly curved channel	Highly curved channel
1	Sudden increase of depth	Sudden increase of depth	Sudden increase of depth
2	Symmetry in lateral velocity	Asymmetry in lateral velocity	Asymmetry in lateral velocity (High)
3	Symmetry in cross section change	Asymmetry in cross section change	Asymmetry in cross section change (High)
4	absence of secondary flow	secondary flow	secondary flow (strong)

occurs.

The point $C/L = 2.38$ is the point at which the strength of two phenomena balance each other in a way that it seems there is no pit or it has no effect on the maximum scour depth. With increasing C/L and consequently depth increase, the intensity of the secondary flow increases such that the effect of mining pit on maximum scour depth will increase and make the raising wing of the Δ-C/L diagram.

4. Conclusions

Gravel mining has always been extremely important due to the rich resources of construction materials. This issue has profound impacts on rivers and their intersecting structures, one of the most important of which is the bed degradation. Moreover, it is crucial to consider that rivers are not usually straight and are generally flow a sinuous trial. In this study, an attempt has been made to investigate and understand the interaction between gravel mining pits and river curvature regarding river bed degradation.

To investigate the interacting effects of river curvature and gravel mining pits on rivers morphology, models of a channel with different curvatures, from a direct channel to a channel with high degree of curvature, were constructed using the a 2D model and the results of the simulations were analyzed.

Morphological study of river beds is a challenge due to the large amount of data produced by a 2D model and it would be extremely difficult to discover the pattern of changes. Therefore, it was decided to focus the morphological effects on a single parameter. By choosing the maximum scour depth as the most destructive morphological effect, comparison has become much understandable, i.e. while enjoy the high accuracy of the results due to the two-dimensional simulation, by focusing the results on this parameter, comparison became more mathematical and quantitative than qualitative and descriptive.

Examination of the results showed that from the direct channel to the channel with higher degree of curvature, the maximum scour depth moves from the center of the cross section toward the outer wall and maximum deposition elevation moves toward the inner wall; in addition, moving of the maximum scour depth along the channel (downstream) is visible.

As can be seen from the results, the maximum scour depth is almost always increased. However, it is clear that a curved channel without a pit will also have more degradation than a straight channel and that is due to the increase in velocity at the outer wall of the bend; therefore, the effect of the mining pit is isolated and investigated separately. For this purpose, a parameter called Δ was defined which was considered equal to the maximum scour depth with the gravel mining pit minus the maximum scour depth without it.

Changes in Δ as the net effect of mining pit in maximum scour depth could be described in three parts; a reducing wing, an extremum and an increasing wing. Increasing the curvature, the value of Δ, from direct channel to channel with light curvature of $C/L = 2.38$ is decreased. At this point, Δ is eventually close to zero which in another word means that there are no difference in maximum scour depth between a channel with a pit and a channel without a pit at this curvature degree. Afterwards, the increasing wing of Δ-C/L diagram is formed.

Inspection of the influent parameters showed that the event is due to two simultaneous phenomena. Decreasing phenomenon which is called smoothing, is an effect of both asymmetry in channel shape and flow velocity which gradually changes "the sudden increase and decrease of depth" (the pit effect) to a smoother edge and cause the mining pit effect on maximum scour depth to decrease. With sharper curvatures, smoothing happens faster and gets softer, therefore the pit net effect on the maximum scour depth is expected to mitigate further. By increasing the curvature, the secondary flow becomes stronger and consequently intensifies the net pit effect on maximum scour depth. After a certain point ($C/L = 2.38$), in which the effect of the both phenomena (smoothing and secondary flow) is in balance, the secondary flow effect which resonates the net pit effect on maximum scour depth will take the lead by curvature increased.

Finally, as described in the previous sections, there are several methods to understand and deal with the effects of gravel mining pit

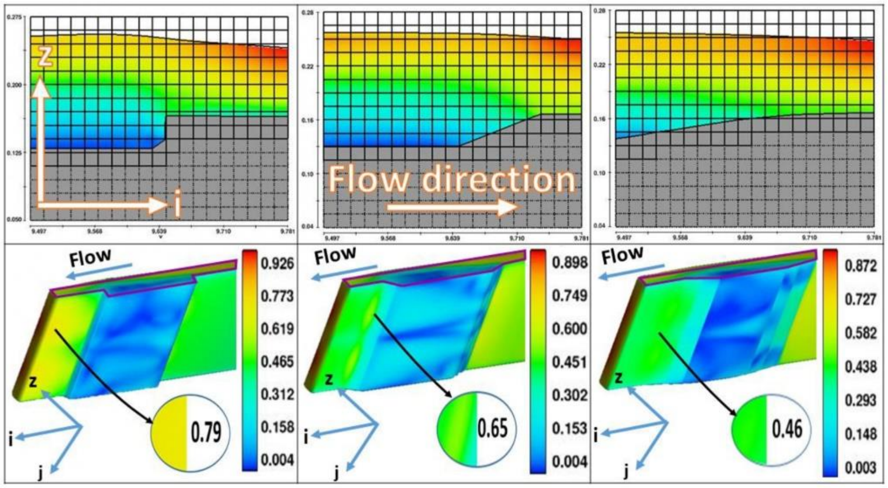


Fig. 10. Velocity changes in contact with the bed downstream the pit using Flow3D.

effects on rivers and their associated structures. One of the most popular and widely used methods is the macroscopic view, which usually examines the extraction of materials in the form of sediment budgets on the entire river ecosystem. These methods have their own merits and are certainly very useful in their place. However, the results of the present study clearly show that the microscopic perspective on the issue of material withdrawal from rivers is also extremely important. Clearly, as the results showed, the location of the gravel mining pits along the river can intensify the bed degradation depth or move it to a great extent. Overall, it seems that by combining these two perspectives and completing knowledge in both sectors, we could have the most appropriate understanding of this phenomenon and adopt the best strategies to manage and reduce its impacts.

CRediT authorship contribution statement

Abedin Mohammad-Hosseinpour: Conceptualization, Formal analysis, Methodology, Software, Writing – original draft. **José-Luis Molina:** Methodology, Supervision, Writing – review & editing. **Ebrahim Jabbari:** Supervision, Writing – review & editing.

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.

References

Arróspide, F., Mao, L., Escauriaza, C., 2018. Morphological evolution of the Maipo River in central Chile: Influence of instream gravel mining. Geomorphology 306, 182–197. https://doi.org/10.1016/j.geomorph.2018.01.019.

Asaeda, T., Sanjaya, K., 2017. The effect of the shortage of gravel sediment in midstream river channels on riparian vegetation cover. River Res Applic. 33 (7), 1107–1118. https://doi.org/10.1002/rra.v33.710.1002/rra.3166.

Ahmadi, H., 1990, Sand and gravel mining from rivers, Ahvaz River Engineering Conference. Ahvaz, Iran.

Boillat, J.-L., Dubois, J., Nilipour, N., 2006. Migration of a Dredging Pit in the Rhone River in River Flow 2006. IAHR, Lisbon, Portugal, pp. 1193–1202.

Calle, M., Alho, P., Benito, G., 2017. Channel dynamics and geomorphic resilience in an ephemeral Mediterranean river affected by gravel mining. Geomorphology 285, 333–346. https://doi.org/10.1016/j.geomorph.2017.02.026.

Chen, D., Acharya, K., and Stone, M., 2008. Modeling of Gravel Mining in the Rio Salado, Arizona. In World Environmental and Water Resources Congress 2008 Ahupua'a Honolulu, Hawaii.

Chen, D., Acharya, K., Stone, M., 2010. Sensitivity analysis of nonequilibrium adaptation parameters for modeling mining-pit migration. J. Hydraul. Eng. 136 (10), 806–811.

Chen, D., Liu, M., 2009. One- and two-dimensional modeling of deep gravel mining in the Rio Salado. World Environmental and Water Resources Congress. Great Rivers Honolulu, Hawaii.

Costea, M., 2018. Impact of floodplain gravel mining on landforms and processes: a study case in Orlat gravel pit (Romania). Environ. Earth Sci 77. https://doi.org/10.1007/s12665-018-7320-y article number 119.

Collins, B.D., Dunne, T., 1989. Gravel harvesting and channel-bed degradation in rivers draining the Southern Olympic Mountains, Washington, U.S.A. Environ. Geol. 13, 213–224.

Dépret, T., Virmoux, C., Gautier, E., Piégay, H., Doncheva, M., Plaisant, B., Ghamgui, S., Mesmin, E., Saulnier-Copard, S., de Milleville, L., Cavero, J., Hamadouche, P., 2021. Lowland gravel-bed river recovery through former mining reaches, the key role of sand. Geomorphology 373, 107493. https://doi.org/10.1016/j.geomorph.2020.107493.

Ghasemi, M., Soltani-Gerdefaramarzi, S., 2017. The Scour bridge simulation around a cylindrical pier using flow-3D. J. Hydrosci. Environ. 1 (2), 46–54.

Gill, M.A., 1994. Hydrodynamics of mining pits in erodible bed under steady flow. J. Hydraul. Eng. 120 (11), 1337–1348.

Jia, Yafei, Sam, S.Y. Wang, "CCHE2D:Two-dimensional Hydrodynamic and Sediment Transport Model for Unsteady Open Channel Flows Over Loose Bed," NCCHE-TR-2001-1, 2001.

Knuuti, K., McComas, D., 2003. Assessment of changes in channel morphology and bed elevation in Mad River, California, 1971–2000.Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Technical Report ERDC/CHLTR-03-16.

Kondolf, G.M., Swanson, M.L., 1993. Channel Adjustments to Reservoir Construction and Gravel Extraction along Stony Creek, California. Environ. Geol. 21, 256–269.

Lee, H.-Y., Fu, D.-T., Song, M.H., 1993. Migration of rectangular mining pit composed of uniform sediments. J. Hydraulic Eng. 119, 64–80.

Luo, X., Zeng, E., Ji, R., Wang, C.H., 2007. Effects of in-channel sand excavation on the hydrology of the Pearl River Delta, China. J. Hydrol. 343 (3–4), 230–239. https://doi.org/10.1016/j.jhydrol.2007.06.019.

Picco, L., Comiti, F., Mao, L., Tonon, A., Lenzi, M.A., 2017. Medium and short term riparian vegetation, island and channel evolution in response to human pressure in a regulated gravel bed river (Piave River, Italy). CATENA 149 (Part 3), 760–769. https://doi.org/10.1016/j.catena.2016.04.005.

Rascher, E., Rindler, R., Habersack, H., Sass, O., 2018. Impacts of gravel mining and renaturation measures on the sediment flux and budget in an alpine catchment (Johnsbach Valley, Austria). Geomorphology 318, 404–420. https://doi.org/10.1016/j.geomorph.2018.07.009.

Raynov, S., Pechinov, D., Kopaliany, Z., 1986. River Response to Hydraulic Structures. Technical Documents in Hydrology. UNESCO, Paris.

Simon, A., 1989. A model of channel response in disturbed alluvial channels. Earth Surf. Proc. Land. 14 (1), 11–26.

Simon, A., Darby, S.E., 2002. Effectiveness of grade-control structures in reducing erosion along incised river channels: the case of Hotophia Creek, Mississippi. Geomorphology 42 (3-4), 229–254.

Simon, A., Rinaldi, M., 2006. Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79 (3 4), 361–383.

Stover, S.C., Montgomery, D.R., 2001. Channel change and flooding, Skokomish River, Washington. J. Hydrol. 243 (3–4), 272–286. https://doi.org/10.1016/S0022-1694(00)00421-2.

Teo, F., Noh N., Ghani, A., Zakaria, N., Chang, C., 2017, River sand mining capacity in Malaysia, 37th IAHR World Congress.

Yao, J., Zhang, D., Li, Y., Zhang, Q.i., Gao, J., 2019. Quantifying the hydrodynamic impacts of cumulative sand mining on a large river-connected floodplain lake: Poyang Lake. J. Hydrol. 579, 124156. https://doi.org/10.1016/j.jhydrol.2019.124156.

Zhai, W., Ding, J., An, X., Wang, Z., 2020. An optimization model of sand and gravel mining quantity considering healthy ecosystem in Yangtze River, China. J. Cleaner Prod. 242, 118385. https://doi.org/10.1016/j.jclepro.2019.118385.

Zhao, Y., Zeng, L., Wei, Y., Liu, J., Deng, J., Deng, Q., Tong, K., Li, J., 2020. An indicator system for assessing the impact of human activities on river structure. J. Hydrol. 582, 124547. https://doi.org/10.1016/j.jhydrol.2020.124547.

Zolghadr, M., Ali Zomorodian, S.M., Sha'bani, R., Azamatulla, H.M., 2021. Migration of sand mining pit in rivers: an experimental, numerical and case study. Measurement 172, 108944. https://doi.org/10.1016/j.measurement.2020.108944.

Capítulo 3 "ARTÍCULO 2"

3.1. Objetivo:

Increasing population, expanding irrigated agriculture areas, and economic development are all driving forces in the world's ever-increasing water demand. Although surface water availability (water in lakes, rivers, and reservoirs) can meet such demand globally, regional variations are substantial, resulting in water stress in certain parts of the world.

To tackle the burgeoning problem of water level decline, it is necessary to take up schemes for water conservation and artificial recharge to groundwater as a priority. The term artificial recharge refers to transfer of surface water to the aquifer by human interference. The natural process of recharging the aquifers is accelerated through percolation of stored or flowing surface water, which otherwise does not percolate into the aquifers. Artificial recharge is also defined as the process by which ground water is augmented at a rate exceeding that under natural condition of replenishment.

In summary, urban development in many arid and semi-arid areas are dependent on groundwater, and over-extraction of this resource would ultimately result in serious problems, e.g., seawater intrusion beneath coastal cities, soil subsidence in urban areas, and groundwater pollution. Given the critical role of groundwater in sustainable city development and water resource management, this research aims to offer an innovative approach to make artificial groundwater recharge achievable using stormwater without expensive sophisticated technology, yet, feasible in cities and usable alongside the traditional or existing stormwater systems.

The Above Paragraphs In Spanish:

El aumento de la población, la expansión de las zonas agrícolas irrigadas y el desarrollo económico son fuerzas impulsoras de la demanda de agua en constante aumento en el mundo. Aunque la disponibilidad de agua superficial (agua en lagos, ríos y embalses) puede satisfacer dicha demanda a nivel mundial, las variaciones regionales son sustanciales, lo que resulta en estrés hídrico en ciertas partes del mundo.

Para abordar el creciente problema de la disminución del nivel del agua, es necesario adoptar como prioridad planes para la conservación del agua y la recarga artificial de las aguas subterráneas. El término recarga artificial se refiere a la transferencia de agua superficial al acuífero por interferencia humana. El proceso natural de recarga de los acuíferos se acelera mediante la percolación del agua superficial almacenada o que fluye, que de otro modo no se filtraría hacia los acuíferos. La recarga artificial también se define como el proceso mediante el cual el agua subterránea aumenta a un ritmo que excede el de las condiciones naturales de reposición.

En resumen, el desarrollo urbano en muchas zonas áridas y semiáridas depende del agua subterránea, y la sobreextracción de este recurso daría lugar en última instancia a graves problemas, por ejemplo, la intrusión de agua de mar debajo de las ciudades costeras, el hundimiento del suelo en las zonas urbanas y la contaminación de las aguas subterráneas. Dado el papel fundamental del agua subterránea en el desarrollo urbano sostenible y la gestión de los recursos hídricos, esta investigación tiene como objetivo ofrecer un enfoque innovador para hacer que la recarga artificial del agua subterránea sea alcanzable utilizando aguas pluviales sin tecnología costosa y sofisticada, pero que sea factible en las ciudades y utilizable junto con los sistemas tradicionales o existentes de aguas pluviales.

3.2. Metodología:

The proposed innovative approach introduces a new concept by modifying and juxtaposing the known techniques to provide the means of artificial recharge of aquifer using stormwater without problems regarding other approaches, in cities. There are three key elements for any artificial recharge technique; firstly, to supply water, secondly to convey it to a recharge facility and finally inject it into the aquifer.

The main goal of any stormwater management system is to ensure the safety of the city and its citizens against floods. Based on this, in almost all the cities around the world, stormwater management systems including channels, pipes, tunnels etc. are al-ready built or are under development in order to collect runoff from different areas and convey it safely to a receiving water body. Therefore, by default, a stormwater collection and conveyance system either exists in cities or is under construction. It should be noted that rainwater collected in this way is usually seen as flood, danger and threat, and the goal of such systems is usually to convey the collected runoff quickly and safely to the first safe place outside the urban environment. Obviously, the collected stormwater in coastal cities, as a source of free and accessible fresh water, is usually discharged into the sea and is wasted. In the proposed approach, this volume of wasted rainwater is used as a free and available source of fresh water to recharge groundwater.

As it is said, rainwater has already been used to artificially recharge groundwater; however, urban environmental conditions and limitations have made these methods not popular or effective. Generally, two methods are used for artificial recharging of rainwater; spreading runoff over a wide area with good permeability, and local injection. Obviously, the first method, while efficient, are very expensive and non-optimal due to the need for large areas in urban environments (where land is scarce and precious), and the second method has always been used locally and in small areas, and is only able to deal with a very small volume of runoff which could not have a consider-able effect on groundwater table.

In the proposed new approach, recharge wells are modified in such a way that work together as a recharge system, and integrate with the existing stormwater management system, especially channels, to change the traditional stormwater network into a recharge facility without affecting its hydraulic function as a stormwater management network; it receives, stores and finally infiltrates runoff into aquifer while the whole network still plays its role protecting city and its residents against flood. The recharge system is built in the vicinity of the channels and below the pavement level on the streets and passages; thus, there would be no need for any space allocation and its cost. There is also no need for special and sophisticated technologies to build them, and along with the modular design, it allows them to be implemented quite fast and inexpensive. And most importantly, it is possible to build them in large numbers in urban environments, and therefore it is possible to deal with a relatively significant volume of rainwater to artificially recharge the aquifer.

The Above Paragraphs In Spanish:

El enfoque innovador propuesto introduce un nuevo concepto al modificar y yuxtaponer las técnicas conocidas para proporcionar medios de recarga artificial de acuíferos utilizando aguas pluviales sin problemas con respecto a otros enfoques, en las ciudades. Hay tres elementos clave para cualquier técnica de recarga artificial; en primer lugar, suministrar agua, en segundo lugar, conducirla a una instalación de recarga y finalmente inyectarla en el acuífero.

El objetivo principal de cualquier sistema de gestión de aguas pluviales es garantizar la seguridad de la ciudad y de sus ciudadanos frente a las inundaciones. En base a esto, en casi todas las ciudades del mundo, ya se han construido o se están desarrollando sistemas de gestión de aguas pluviales, incluidos canales, tuberías, túneles, etc., para recoger la escorrentía de diferentes áreas y transportarla de forma segura a una masa de agua receptora. . Por lo tanto, por defecto, existe un sistema de recolección y transporte de aguas pluviales en las ciudades o está en construcción. Cabe señalar que el agua de lluvia recolectada de esta manera generalmente se considera una inundación, un peligro y una amenaza, y el objetivo de dichos sistemas suele ser transportar la escorrentía recolectada de manera rápida y segura al primer lugar seguro fuera del entorno urbano. Obviamente, las aguas pluviales recogidas en las ciudades costeras, como fuente de agua dulce gratuita y accesible, normalmente se vierten al mar y se desperdician. En el enfoque propuesto, este volumen de agua de lluvia desperdiciada se utiliza como fuente gratuita y disponible de agua dulce para recargar el agua subterránea.

Como se dice, el agua de lluvia ya se ha utilizado para recargar artificialmente las aguas subterráneas; sin embargo, las condiciones y limitaciones ambientales urbanas han hecho que estos métodos no sean populares ni efectivos. Generalmente se utilizan dos métodos para la recarga artificial de agua de lluvia; Distribuir la escorrentía en una zona amplia con buena permeabilidad e inyección local. Evidentemente, el primer método, aunque eficiente, es muy costoso y no óptimo debido a la necesidad de grandes superficies en entornos urbanos (donde el suelo es escaso y valioso), y el segundo método siempre se ha utilizado localmente y en áreas pequeñas , y sólo es capaz de hacer frente a un volumen muy pequeño de escorrentía que no podría tener un efecto considerable sobre el nivel freático.

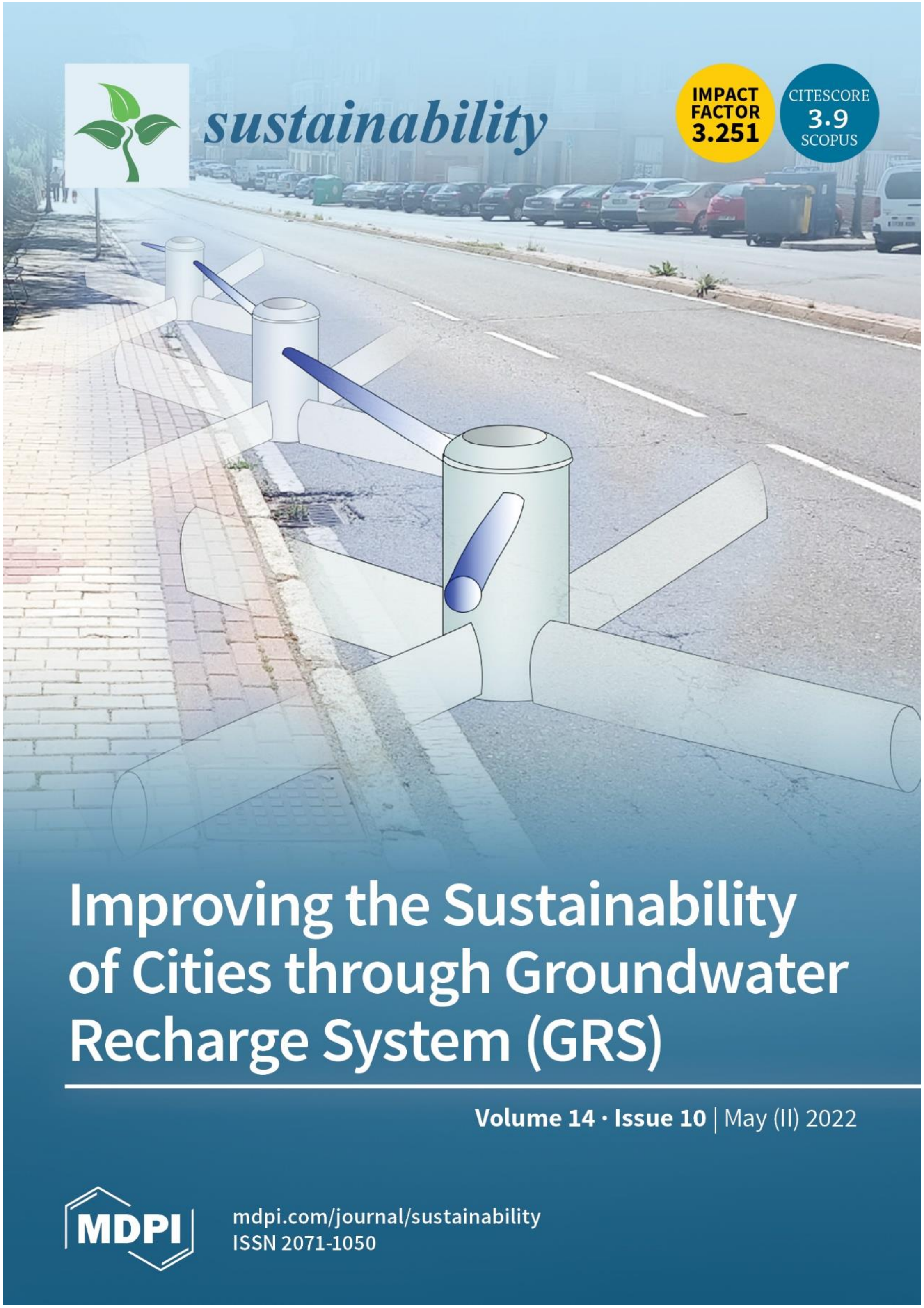
En el nuevo enfoque propuesto, los pozos de recarga se modifican de tal manera que funcionen juntos como un sistema de recarga y se integren con el sistema de gestión de aguas pluviales existente, especialmente los canales, para cambiar la red tradicional de aguas pluviales en una instalación de recarga sin afectar su función hidráulica como una red de gestión de aguas pluviales; recibe, almacena y finalmente infiltra la escorrentía en el acuífero mientras toda la red sigue desempeñando su función de proteger a la ciudad y a sus residentes contra las inundaciones. El sistema de recarga se construye en las cercanías de los canales y debajo del nivel del pavimento en las calles y pasajes; por lo tanto, no habría necesidad de asignar espacio ni su costo. Tampoco se necesitan tecnologías especiales y sofisticadas para construirlos y, junto con el diseño modular, permite una implementación bastante rápida y económica. Y lo más importante, es posible construirlos en grandes cantidades en entornos urbanos y, por tanto, es posible aprovechar un volumen relativamente importante de agua de lluvia para recargar artificialmente el acuífero.

3.3. resultados:

In general, the new proposed system which is called Groundwater Recharge System (GRS), works by modifying the existing stormwater management network and using it as a collector, supplier, and conveyer of water source to enter the recharge systems installed in its vicinity and through its length, while their main objective, which is to ensure safety against floods, remains intact. The design and implementation of the mentioned system in the study area showed that even in the worst-case scenario, when this system is filled only once a year, it will be able not only to resolve many of the adverse effects of groundwater overuse, but also will be able to deal with the effects of climate change impacts such as precipitation reduction and rising sea levels. Along with all these advantages, perhaps the most important features of the proposed facility are its cheap and fast construction along with the lack of need for complex technologies.

The Above Paragraphs In Spanish:

En general, el nuevo sistema propuesto, denominado Sistema de Recarga de Agua Subterránea (GRS), funciona modificando la red de manejo de aguas pluviales existente y utilizándola como fuente colectora, suministradora y transportadora de agua para ingresar a los sistemas de recarga instalados en sus cercanías y a través de su longitud, mientras que su principal objetivo, que es garantizar la seguridad contra las inundaciones, permanece intacto. El diseño e implementación del sistema mencionado en el área de estudio demostró que incluso en el peor de los casos, cuando este sistema se llene sólo una vez al año, podrá no sólo resolver muchos de los efectos adversos del uso excesivo del agua subterránea, sino también También podrá hacer frente a los efectos del cambio climático, como la reducción de las precipitaciones y el aumento del nivel del mar. Junto con todas estas ventajas, quizás las características más importantes de la instalación propuesta sean su construcción rápida y económica, además de la ausencia de necesidad de tecnologías complejas.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Improving the Sustainability of Urban Water Management through Innovative Groundwater Recharge System (GRS)

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Abstract: Negative impacts of groundwater overuse have always been one of the problems of modern cities in arid and semi-arid regions; rapid population growth and climate change have also exacerbated these problems in many areas. One of the best approaches to deal with the impacts of these phenomena (soil subsidence, decline in groundwater quality, and seawater intrusion) is to artificially recharge water into aquifers and raise the groundwater level. In this paper, an innovative solution called Groundwater Recharge Systems (GRS) is proposed with high efficiency, low cost, and fast implementation capability to address these problems. The proposed solution also has the capability of being constructed in urban environments without the need to allocate any spacious land or the need to use any sophisticated technologies. The study of implementing the proposed groundwater recharge systems in the study area showed that the performance of this system, even in worst-case scenarios, will be very significant even considering climate change impacts such as seawater level rise and decline in precipitation.

Keywords: city development; sustainability; groundwater recharge; stormwater management network

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1. Introduction

Increasing population, expanding irrigated agriculture areas, and economic development are all driving forces in the world's ever-increasing water demand. Although surface water availability (water in lakes, rivers, and reservoirs) can meet such demand globally, regional variations are substantial, resulting in water stress in certain parts of the world [1]. The Sahel, South Africa, the Central United States, Australia, India, Pakistan, and North-East China are examples of regions facing recurrent water stress [2]. Over 2 billion people (35 percent of the world's population) are expected to be suffering from acute water scarcity [3].

In arid and semi-arid locations where surface water resources are mostly insufficient or inadequate to meet the needs of the community, groundwater is a critical means of attaining freshwater for more than half of the world's population needs [1,4,5]. Approximately 70% of the world's groundwater resources are used for agriculture [6]. Agriculture (89%) is the most common use of groundwater in India, followed by home (9%) and industrial (2%) usages [7,8]. According to the Ministry of Water Resources of the People's Republic of China (2018) and the Water Resources Department of Xinjiang (2018), 93 percent of water resources in Xinjiang province in arid Northwest China were used for agriculture, with groundwater accounting for more than 30 percent of water supply [9].

During the last 50 years, the water demand in Europe has risen gradually because of the increase in the human population. Around 55% of the world's human population lives in urban areas. The population living in 17 capital cities of the EU was 71.1 million in 2014, and a stable increase in population was observed in all large European cities in the last decade [10]. This has led to a general decrease in renewable groundwater resources by 24% per person in Europe [11].

An indispensable element in preventing such hazards is groundwater recovery in urban areas, with regard to both its quantity and chemical status assessment. According to the assessment standards determined by the Water Framework Directive (WFD) [12], poor chemical status was observed in 9% of groundwater bodies, and, in 75% of cases, the main reason was the decrease in groundwater levels [13].

The need for groundwater extraction, and its consequence depletion, are caused by seasonal fluctuations in water availability, drought-prone conditions, and insufficient rainfall [14]. Altogether, continuous groundwater pumping is the primary source of groundwater depletion. Groundwater depletion would lead to negative repercussions such as increased pumping costs, deterioration of water quality, reduction in water in streams and lakes, saline water intrusion in coastal cities, and land subsidence. While these consequences are variable, they ultimately occur to some extent with any groundwater use [15]. As with other natural resources, society must consider the advantages and disadvantages of using them.

To tackle the burgeoning problem of water level decline, it is necessary to take up schemes for water conservation and artificial recharge of groundwater as a priority. The term artificial recharge refers to transfer of surface water to the aquifer by human interference. The natural process of recharging the aquifers is accelerated through percolation of stored or flowing surface water, which otherwise does not percolate into the aquifers. Artificial recharge is also defined as the process by which groundwater is augmented at a rate exceeding that under natural condition of replenishment. Therefore, any man-made facility that adds water to an aquifer may be considered as artificial recharge [16].

The concept of rainwater harvesting (RWH) is not new, and it is widely employed to address water scarcity and urban flooding in many regions of the world [17]. It is a significant source of groundwater recharge that can be used for both drinking and non-drinking applications, such as irrigation and farming [18–23]. According to history, expanding global interest in rainwater harvest arose in the 1980s, and the approach is now receiving more attention and is equally popular in the western and eastern parts of the world [24]. The number of studies on rainwater harvesting has grown at an exponential rate during the last four decades, and includes Australia [25], Brazil [26], China [27,28], Greece [29], India [30,31], Bangladesh [32], Iran [33,34], Pakistan [35–37], Indonesia [38], Hawaii [39], and Kenya [40].

Techniques used for artificial groundwater recharge broadly fall under the two following categories: direct and indirect methods. Direct methods involve surface spreading techniques and sub-surface techniques, and indirect methods include induced methods and aquifer modification methods [41].

Surface spreading techniques, which involve flooding, ditch and furrows, recharge basins, runoff conservation structures (bench terracing, contour bunds and contour trenches, gully plugs, nalah bunds, check dams, percolation ponds), and stream modification/augmentation are aimed at increasing the contact area and residence time of surface water over the soil to enhance the infiltration and to augment the groundwater storage in phreatic aquifers [41]. The downward movement of water is governed by a host of factors including vertical permeability of the soil, presence of grass or entrapped air in the soil zone, and the presence or absence of limiting layers of low vertical permeability at depth. Changes brought about by physical, chemical, and bacteriological influences during the process of infiltration are also important in this regard [42].

Important considerations in the selection of sites for artificial recharge through surface spreading techniques include that: (a) the area should have gently sloping land without gullies or ridges; (b) the aquifer being recharged should be unconfined, permeable, and sufficiently thick to provide storage space; (c) the surface soil should be permeable and have a high infiltration rate; (d) the vadose zone should be permeable and free from clay lenses; (e) groundwater levels in the phreatic zone should be deep enough to accommodate the recharged water so that there is no water logging; and (f) the aquifer material should have moderate hydraulic conductivity so that the recharged water is retained for sufficiently long periods in the aquifer and can be used when needed [41,42]. The main problems with implementing these methods in cities are the need for spacious lands and special topographies, which are rarely available in cities and developed areas or are very expensive to obtain.

Sub-surface techniques, which include injection wells (recharge wells), gravity head recharge wells, and recharge pits and shafts, aim at recharging deeper aquifers that are overlain by impermeable layers, preventing the infiltration from surface sources to recharge them under natural conditions [41,42]. The main problem with these methods is that they are very localized; therefore, only limited artificial recharge will occur through a localized structure, and subsequently will result in insignificant impacts.

Indirect methods for artificial recharge to groundwater do not involve direct supply of water for recharging aquifers but aim at recharging aquifers through indirect means. The most common methods in this category are induced recharge from surface water sources and aquifer modification techniques [41,42]. This approach involves induced recharge from surface water and aquifer modification techniques such as bore blasting methods, hydro-fracturing method, jacket well technique and fracture seal cementation, and pressure injection grouting; they mostly deal with aquifer capacity modification and between-aquifer water transfer, which are extremely expensive and mostly unusable in cities.

In summary, urban development in many arid and semi-arid areas is dependent on groundwater, and over-extraction of this resource would ultimately result in serious problems, e.g., seawater intrusion beneath coastal cities, soil subsidence in urban areas, and groundwater pollution. Given the critical role of groundwater in sustainable city development and water resource management, this research aims to offer an innovative approach to make artificial groundwater recharge achievable using stormwater without expensive sophisticated technology, yet, feasible in cities and usable alongside the traditional or existing stormwater systems.

2. Materials and Methods

2.1. Case Study

Kish is a small island in the Persian Gulf, 19 km off Iran's mainland, with a 91 km^2 surface area, a 40 km outer perimeter, and a nearly circular form as shown in Figure 1. The surface of the island is flat, with no mountains or even high hills. Its highest surface inclination extends from the airport, built in the center on an elevated area 35–40 m above sea level, to the shores [43].

Figure 1. Location of Kish Island, [44]: Google Maps, 2022. Kish Island, 1:33,333 and 1:500. Google Maps (online) Available through: Polytechnic School of Ávila https://www.google.com/maps (accessed on 24 April 2022).

Based on climate classification, in which the combined effect of precipitation and temperature are considered, Kish is a very dry area and its climatic condition generally is arid and semi-tropical. According to statistics, the average rainfall is about 180 mm, (65% in winter, 28% in fall, and 14% in the summer) and mean annual temperature is 26.6 °C [43,45].

Kish Island has the long sunshine hours—except for coastal areas of southeast and several other Persian Gulf islands—that is, about 3100 h a year; therefore, the annual evaporation is about 1650 mm, which is more than nine times the rainfall [43].

Considering the 20-year development perspective of Kish Island in various aspects, including tourism development and turning it into the top tourism destination for families, scientific-educational-research hub, sustainable development model using new technologies, and the most suitable place for investment in the Persian Gulf region, it can be expected to be accompanied by an increase in the need for drinking water for residents and tourists, as well as industrial development needs [43]. This increase in water demand along with climate change could lead to increase in water stress and consequent groundwater table depletion.

The touristic zone in the northeastern part of the island with an area of about 852 hectares is fully developed with moderate density, and involves residential areas, commercial and recreational centers, and has all the criteria required for this research: a developed urban area, adjacent to the sea, and a freshwater lens.

2.2. Methods

The proposed innovative approach introduces a new concept by modifying and juxtaposing the known techniques to provide the means of artificial recharge of aquifers using stormwater, without problems regarding other approaches, in cities. There are three key elements for any artificial recharge technique: firstly, to supply water, secondly, to convey it to a recharge facility, and finally, inject it into the aquifer.

The main goal of any stormwater management system is to ensure the safety of the city and its citizens against floods. Based on this, in almost all the cities around the world, stormwater management systems including channels, pipes, tunnels, etc., are already built or are under development in order to collect runoff from different areas and convey it safely to a receiving water body. Therefore, by default, a stormwater collection and conveyance system either exists in cities or is under construction. It should be noted that rainwater collected in this way is usually seen as a flood danger and threat, and the goal of such systems is usually to convey the collected runoff quickly and safely to the first safe place outside the urban environment. Obviously, the collected stormwater in coastal cities, as a source of free and accessible freshwater, is usually discharged into the sea and is wasted. In the proposed approach, this volume of wasted rainwater is used as a free and available source of freshwater to recharge groundwater.

As it is said, rainwater has already been used to artificially recharge groundwater; however, urban environmental conditions and limitations have made these methods unpopular or ineffective. Generally, two methods are used for artificial recharging of rainwater: spreading runoff over a wide area with good permeability, and local injection. Obviously, the first method, while efficient, is very expensive and non-optimal due to the need for large areas in urban environments (where land is scarce and precious), and the second method has always been used locally and in small areas, and is only able to deal with a very small volume of runoff, which could not have a considerable effect on the groundwater table.

In the proposed new approach, recharge wells are modified in such a way that they work together as a recharge system, and integrate with the existing stormwater management system, especially channels, to change the traditional stormwater network into a recharge facility without affecting its hydraulic function as a stormwater management network; it receives, stores, and finally infiltrates runoff into aquifers while the whole network still plays its role protecting a city and its residents against floods. The recharge system is built in the vicinity of the channels and below the pavement level on the streets and passages; thus, there would be no need for any space allocation and its cost. There is also no need for special and sophisticated technologies to build them, and along with the modular design, it allows them to be implemented quite fast and inexpensively. Most importantly, it is possible to build them in large numbers in urban environments, and therefore it is possible to deal with a relatively significant volume of rainwater to artificially recharge the aquifer. A schematic view of the proposed system and its components is presented in Figure 2.

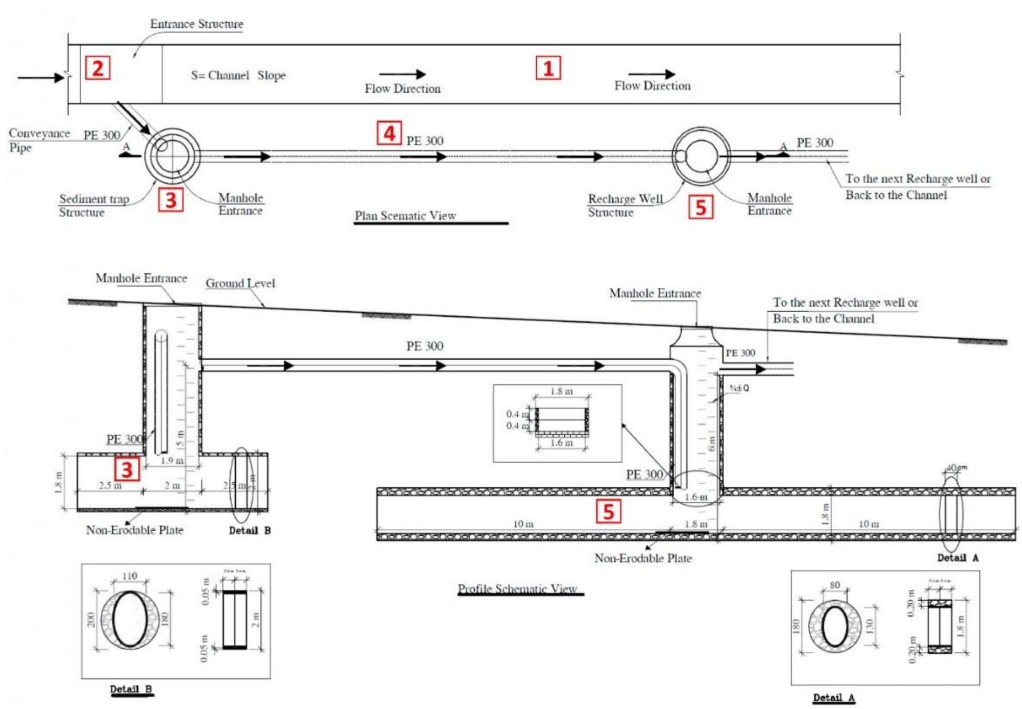

Figure 2. Schematic view of the recharge wells system.

In the following, each element of the recharge system and how they work are introduced as numbered on the figure.

1. The existing channel, while still playing its main role as a collector and flood conveyer in the stormwater management network, will also play a minor role as supplier of water for artificial recharge.
2. The entrance structure has the role of diverting water from the existing channel to the recharge system by considering two crucial criteria: always, and even in low flows, it should be able to supply water for the recharge system and at the same time should not affect the hydraulic performance of the existing channel. Figure 3 shows a potential design for the entrance structure.
3. The sediment trap structure acts as an interface between the stormwater network and recharge wells. This structure takes water from the existing channel, stores it, and increases retention time, trapping sediments, trash, and pollution to some extent. This structure is made of prefabricated concrete rings and is modular. The proposed bottom storage is cylindrical in shape with 1.1×1.8 m^2 oval concrete rings and a length of 7 m, which creates a volume of about 12 m^3. Due to the role of this structure, its entrance has been proposed with large dimensions, and circular concrete rings with

an inner diameter of 1.9 m, to provide better operation and maintenance conditions. Since the exit point of this structure is about 5 m above its floor, 8.5 m^3 are added to its volume and its total volume reaches 20.5 m^3.

4. Conveyance pipes are responsible for transferring water between the channel and the recharge system as well as between the structures themselves.
5. Recharge wells are almost similar to sediment trap structures in terms of shape, with different dimensions and purpose. The proposed galleries are of cylindrical shape with 1.3 × 0.8 m^2 oval concrete rings and a total length of 40 m, in the form of four interconnected crossed cylinders with 10 m length each. This creates a volume of about 45 m^3 per recharge well. A recharge system is considered to be include up to three recharge wells according to the local conditions, which will eventually provide a volume of about 135 m^3 per recharge system. A schematic view of a recharge system with three recharge wells is demonstrated in Figure 4.

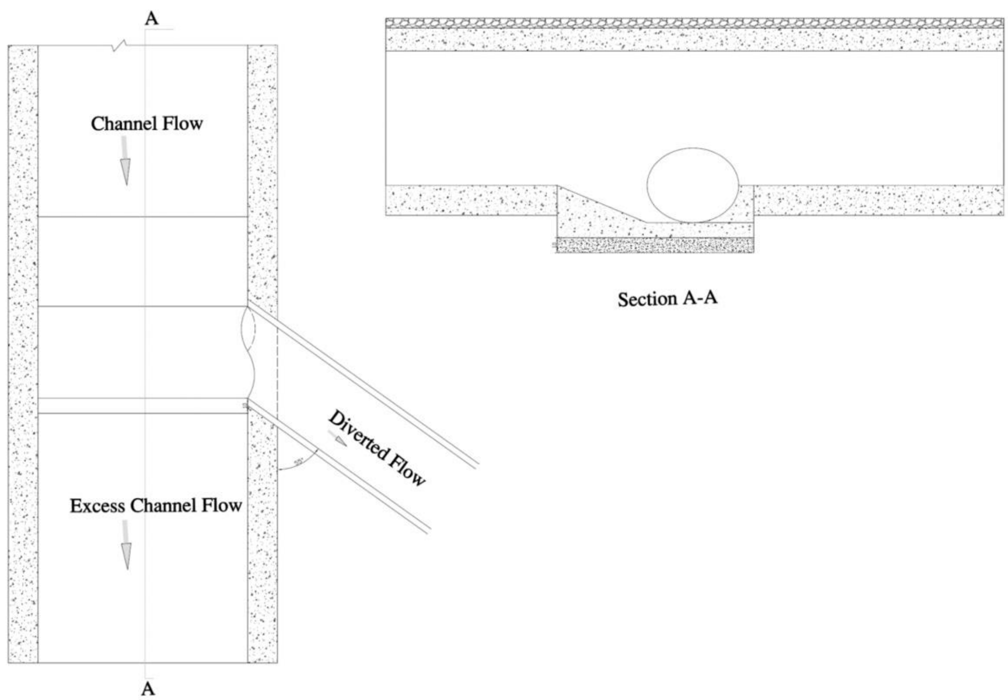

Figure 3. Schematic view of a potential design of the entrance structure.

In terms of performance, these modified recharge wells are actually a combination of conventional recharge wells and permeable tanks. The proposed technique is similar in form to recharge wells and benefits from its easy implementation and low cost; on the other hand, they function like permeable tanks by providing adequate storage volumes, considering the low rate of water infiltration into the soil layers, store water, and inject it at the required duration of time into the soil and finally the aquifer.

It should be noted that recharge wells are usually connected directly to the aquifer, and because of their limited penetration rate, they usually are not capable of recharging a significant volume of water into aquifers in a short time. Thus, usually in case of rainfall events and in exposure to large volumes of water, they will cause flooding in the surrounding street for a long period of time, if not fail totally. Moreover, it should be said that direct injection of water into the aquifer without proper filtration will cause possible contamination of the groundwater, while with the infiltrating water through the soil layers, pollution will be removed to a great extent before recharging the aquifer.

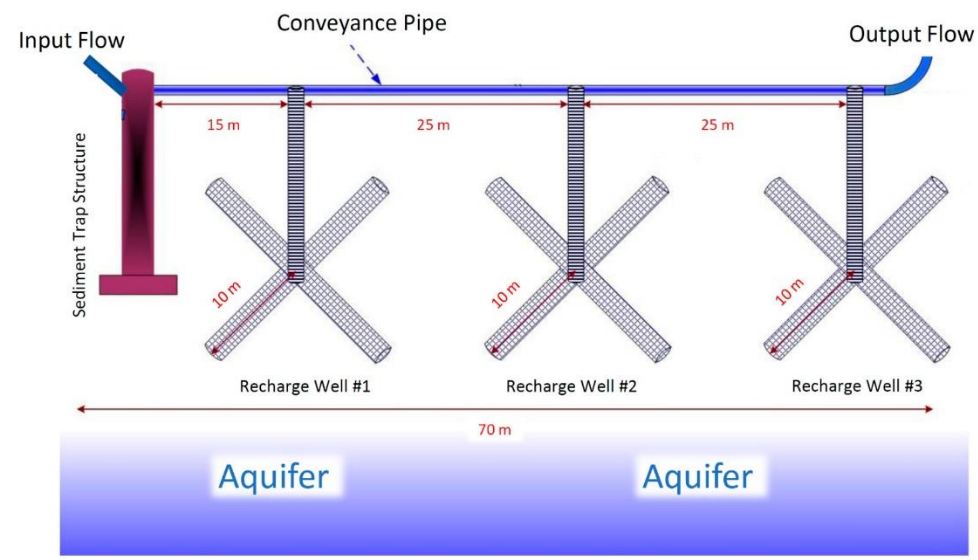

Figure 4. Schematic view of the proposed recharge system.

3. Results

As explained earlier, one of the most important parts of any recharge system is the water supply. Therefore, the tourist zone of Kish Island is surveyed regarding the stormwater network, and it is determined that the stormwater management network is not developed yet, but its design has been completed and is awaiting construction. Figure 5 shows the overview of the designed channels of the mentioned stormwater network.

Table 1 summarizes the results of the precipitation of Kish Island based on its synoptic meteorological station.

The design results show that the main channel, which is shown in red color in Figure 5, with a catchment area of 350 ha, is the most important channel of this network, and about 40% of the catchment area and consequently runoff of the study area drains through it to the sea. The network is designed for 2 years return period rainfall and as presented in Table 2, the main channel is about 3.3 km long and its dimensions range from 1.0×0.8 m^2 to 2.5×1.2 m^2.

Table 1. Meteorology precipitation summary of Kish Island.

Parameter	Fall			Winter			Spring			Summer			Yearly
	October	November	December	January	February	March	April	May	June	July	August	September	
min	0	0	0	0	0	0	0	0	0	0	0	0	24.8
Ave	2.35	8.32	46.7	35.83	28.58	36.1	8.67	1.27	5.03	1.68	1.31	0.57	175.54
max	64.8	57.3	189.6	126.3	209.6	273.3	67.7	30.2	100	56	38	19.5	496.1
deviation	11.26	13.95	53.97	36.28	45.6	57.85	16.51	5.22	20.33	9.46	6.45	3.29	116.79
%	1.34	4.74	26.6	20.41	16.28	20.56	4.94	0.72	2.86	0.96	0.75	0.32	100
Sum		57.37			100.51			14.97			3.56		100
%		32.68			57.25			8.53			2.03		100

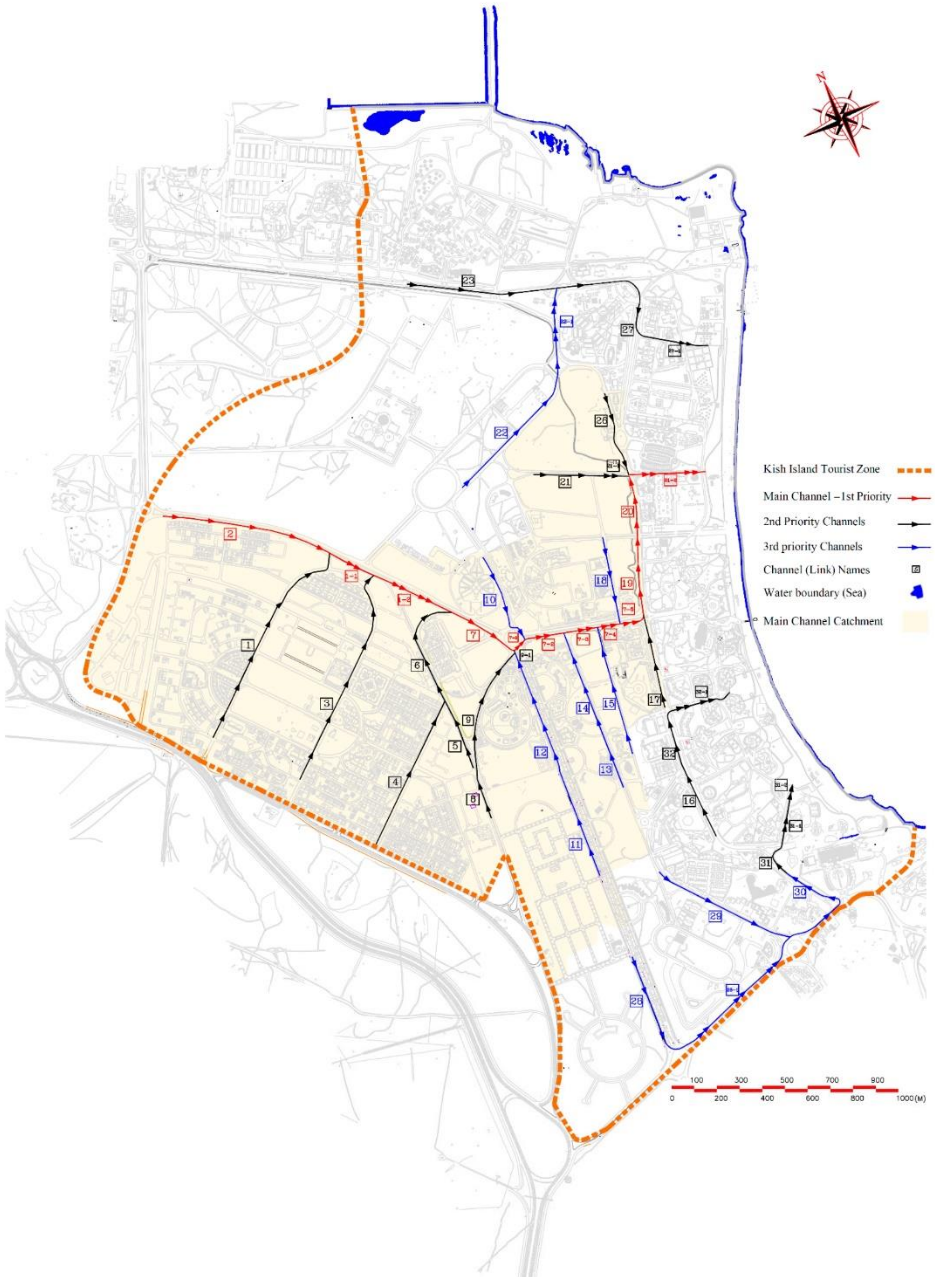

Figure 5. Designed stormwater management network.

Table 2. Main channel characteristics.

	Channel	Area (ha)	Length (m)	Width (m)	Height (m)	Slope (%)	Q (m^3)
1	2	37	761	1.00	0.80	0.30	0.89
2	1-1	77	216	1.10	1.00	0.50	1.60
3	1-2	112	380	1.10	1.00	0.85	2.15
4	7	169	324	1.50	1.00	0.75	3.22
5	7-1	239	67	1.50	1.00	1.20	4.03
6	7-2	253	174	1.50	1.00	1.50	4.26
7	7-3	274	151	1.50	1.00	1.50	4.68
8	7-4	283	101	1.50	1.00	1.20	4.84
9	7-5	303	122	2.00	1.00	1.20	5.22
10	19	317	373	2.50	1.20	0.30	5.40
11	20	322	256	2.50	1.20	0.35	5.42
14	21-2	350	338	2.50	1.20	0.35	5.86

In order to determine the place of artificial recharge facilities, characteristics such as distance to groundwater aquifer, hydraulic gradient, and permeability of soil layers are considered. Accordingly, in the vicinity and parallel to the channel route, 33 recharge systems, each with 3 recharge wells for every 100 m of the channel length, were implemented; the results are shown in Figure 6. It has also been considered to keep a minimum depth of 1 m distance from groundwater (thickness of the unsaturated layer) so that proper filtration could happen alongside fast penetration.

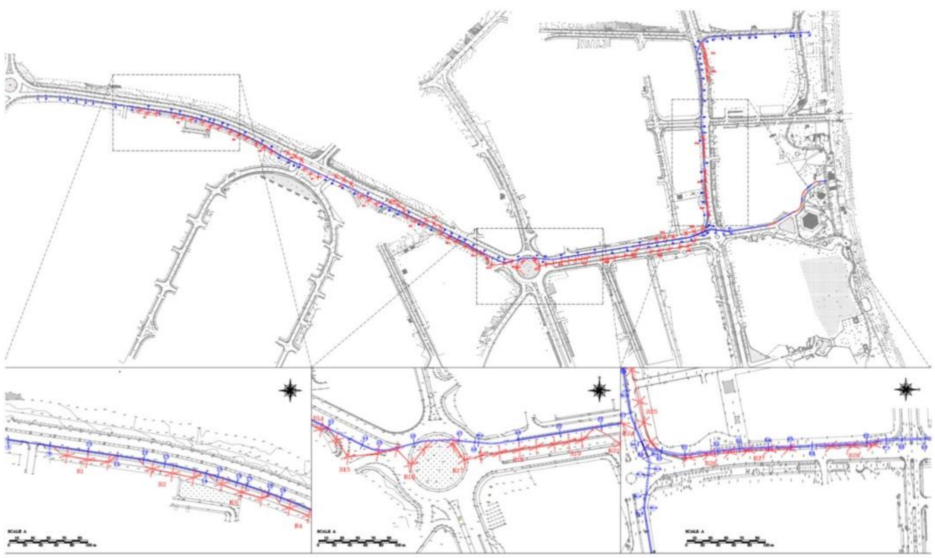

Figure 6. Proposed locations of recharge systems for the main channel.

The water infiltration rate by each well is calculated through the Darcy's Law (1856):

$$Q = K \times A \times I, \quad (1)$$

where in:

Q = infiltration rate per well (m^3/s)

K = permeability coefficient (m/s)
A = cross section area (m^2)
I = hydraulic gradient

Infiltration happens through walls and horizontal galleries of each well. Since the amount of permeability coefficient in each channel route (3.3 km) is different, recharge rates are calculated separately for each recharge system and then a total amount is estimated. The recharge rate of a recharge system based on average values is calculated as follows.

The cross-sectional area from which the water will infiltrate is calculated separately for the wells and horizontal galleries. The depth of an average well is about 4 m, and its diameter is 1.8 m. Considering three wells in each system, the total cross-section of walls in each system is about 68 m^2. Each well has four horizontal galleries; with 10 m length and 2 m outer diameter, the total cross-section of each well is 251 m^2. As infiltration is heavily affected by gravity's downward force, the infiltration flow is estimated to be about 0.6 of the cross section; therefore, the cross-sectional area of the galleries of each well will be about 151 m^2. Altogether, the total cross-sectional area of a well and its galleries is about 174 m^2, which will be 522 m^2 for the whole recharge system.

Surface water infiltration is highest in the northeastern strips as well as in the southern part of the island due to the medium-to-high permeability of these areas. Most of the island has moderate permeability and, due to the constant spatial distribution of rainfall, infiltration rate is also moderate [46]. The permeability coefficient (K) was estimated in each recharge system according to the results of lugeon permeability tests in boreholes close to them. The average permeability in the proposed recharge systems is considered 2.4×10^{-5} ms^{-1}. Consequently, the infiltration rate for this recharge system will be about 12.5 Ls^{-1}. With the same calculations and assumptions, the recharge rates for all 33 proposed recharge systems are calculated and presented in Table 3.

Table 3. Infiltration rates of proposed recharge systems.

First Priority				Second Priority			
Recharge System	**Depth (m)**	**Permeability (ms^{-1})**	**Infiltration Rate (Ls^{-1})**	**Recharge System**	**Depth (m)**	**Permeability (ms^{-1})**	**Infiltration Rate (Ls^{-1})**
R21	6.5	3.00×10^{-5}	15.7	R1	5	1.50×10^{-5}	7.8
R22	6.5	4.50×10^{-5}	23.5	R2	4.5	1.50×10^{-5}	7.8
R23	5	4.50×10^{-5}	23.5	R3	4	1.20×10^{-5}	6.3
R24	4.5	4.50×10^{-5}	23.5	R4	4	1.20×10^{-5}	6.3
R25	4.5	4.50×10^{-5}	23.5	R5	4.5	1.30×10^{-5}	6.8
R26	4.5	4.50×10^{-5}	23.5	R6	4.5	1.40×10^{-5}	7.3
R27	4.5	4.50×10^{-5}	23.5	R7	4.5	1.40×10^{-5}	7.3
R28	4.5	4.50×10^{-5}	23.5	R8	4	1.40×10^{-5}	7.3
R29	4	4.50×10^{-5}	23.5	R9	4	1.40×10^{-5}	7.3
R30	4	4.50×10^{-5}	23.5	R10	4	1.30×10^{-5}	6.8
R31	4	4.50×10^{-5}	23.5	R11	4	1.30×10^{-5}	6.8
R32	4	3.00×10^{-5}	15.7	R12	6	1.20×10^{-5}	6.3
R33	4	3.00×10^{-5}	15.7	R13	5.5	1.20×10^{-5}	6.3
				R14	5	1.30×10^{-5}	6.8
				R15	4.5	1.30×10^{-5}	6.8
				R16	4.5	1.30×10^{-5}	6.8
				R17	4.5	1.30×10^{-5}	6.8
				R18	4.5	1.30×10^{-5}	6.8
				R19	4.5	1.30×10^{-5}	6.8
				R20	5.5	1.50×10^{-5}	7.8

The total infiltration rate of the proposed stormwater recharge systems is estimated to be about 422 Ls^{-1} and its total storage volume will be about 17,500 m^3.

4. Discussion

Groundwater resources play an important role in human life and their environment, especially for coastal cities and islands due to their proximity to seawater and high possibility of saline water intrusion and consequent groundwater pollution. Kish Island is one of the few islands in the Persian Gulf that has fresh and extractable groundwater resource. However, research shows that this valuable resource is endangered for a couple of reasons: natural causes (such as rising sea levels and declining precipitation) and human activities (such as over-extraction of aquifers due to increasing water needs because of population growth and industrialization, as well as land-use change and continuous development).

In coastal aquifers, there is a high risk of seawater intrusion into groundwater resources and in this regard, the study of the vulnerability of groundwater resources are very important in determining the vulnerabilities and sensitive points of the aquifer. In a model with neural network training using synthetic data obtained from numerical modeling of freshwater lenses, a salinity water risk identification and risk management program for Kish Island was investigated to deal with changes [47]. In another study, the distribution map of electrical conductivity and water level in Kish Island was drawn by the minimum curvature method, and then the relationship between electrical conductivity and topography of the area was established. The results show that the amount of relative electrical conductivity is reduced; in other words, in the center of the island with a height of 33 m, the water level has reached a maximum height of 28.24 m and the relative electrical conductivity has reached a very low minimum of 0.046 [48]. More importantly, studying of Kish Island groundwater aquifer vulnerability using drastic modification model for the conditions of this coastal aquifer including parameter of sea water level difference with water stability level and point to sea distance, as well as recorded and sampled data on water quality of island wells, shows that 34.1% of the Kish Island aquifer has a very high vulnerability potential, 48.1% has a high vulnerability potential, and 17.8% has a medium vulnerability potential [46].

Due to these circumstances, the proposed artificial groundwater recharge system is able to supply freshwater to the aquifer in order to increase water quality and repel saline seawater, while increasing the amount of rainwater harvested. In this regard, studying statistics and data on the average rainfall and groundwater consumption can be informative.

Approximately, about 20% of the Kish Island's precipitation (40 mm per year, equivalent to 3.6 MMm^3 annually) penetrates the porous soil and recharges the freshwater lens of the island. According to existing plans, about 40 to 50 percent of this volume (16 to 20 mm annually, equivalent to 1.4 to 1.8 MMm^3 annually) is extracted through existing wells. Therefore, the net recharge rate of the aquifer (total recharge minus extract) will be equal to 10 to 12% of the total annual rainfall of Kish Island (20 to 24 mm per year, equivalent to 1.8 to 2.2 MMm^3 per year) [45,49,50].

In this regard, the study area with an area of 350 ha is approximately 4% of the total area of the island, and in general, this ratio can be expanded to net infiltration volume and give an estimation of about 70,000 m^3 per year for this area. Regardless of the water infiltration rate and volume, the storage volume supplied by the proposed system is about 17,500 m^3, equivalent to 25% of the area's net infiltration volume. Generally, about 80% of rainfall volume is either evaporated or discharged into the sea, which will be about 14.4 MMm^3 on average for the whole island and 570,000 m^3 for the study area. This calculation shows that in a normal water year, it is theoretically possible to fill the system more than 30 times. Although this scenario might be too optimistic, it is quite obvious that there is enough water to fill this system, and even in a pessimistic scenario one can expect that this system will be filled up at least three times if precipitation occurs three times a year. This will mean more than 50,000 m^3 of recharge to aquifer, which is a 75% rise in the current net amount.

There are two important points about the performance of this system. Firstly, the runoff in urban areas is expected to be collected and transferred through the stormwater management network to the outlet; since the stormwater network of the project area will be modified to also act as the collector and supplier of the recharge system, this indicates that it is actually a realistic estimation that a large portion of this water volume is available to the proposed recharge system. Secondly, Kish Island enjoys long sunny hours (up to 325 h per month in summer) and high temperatures (up to 36 °C in winter and up to 46 °C in spring), which generally means a very high evaporation rate; water stores in this system in underground galleries, and therefore it is safe from sunlight and evaporation, which is a big advantage for using this system in such conditions.

Environmental changes resulting from climate change including saline seawater intrusion, and changes in the precipitation, are of high sensitivity for groundwater management of any small island such as Kish Island. Simulations to determine the abstraction values and to control the advance of saline water towards the freshwater lens of the island show the importance of groundwater recharging in the study area. These simulations compare two important changes in rising seawater level and changes in precipitation in five scenarios: seawater level 1 m rise, 20% increase in the net recharge due to increased rainfall, seawater level 1 m rise and increase by 20% in the net recharge due to increased rainfall, 15% decrease in the net recharge due to decreased rainfall, and seawater level 1 m rise and decrease by 15% in the net recharge due to decreased rainfall. The research was performed based on the administrative areas of Kish Island and the results in different scenarios for the northeastern parts of the island, such as District 4 (case study area of this research), were worse than other parts [51].

The simulation results showed that the island freshwater lens thickness increased by 9.8% for Scenario 2, where the net recharge rate increased by 20%, and for Scenario 4, where the net recharge rate decreased by 15%, the lens thickness decreased by 9% [51]. Since the proposed recharge system is capable of adding a 24% to the net recharge rate only by filling up once a year, it is an easy conclusion that in the current situation (without increase in the precipitation), an increase in the thickness of the island's freshwater lens by 10% could be expected. Furthermore, even in the net recharge rate reduction scenario, this system can compensate the decrease in precipitation and net recharge rate by filling only once a year, which is very pessimistic, while one could easily expect this system to fill up at least a few times during the year.

Sea level rise can significantly alter coastlines, especially in low-grade areas. Comparing the current conditions and the scenario of increasing the sea level by 1 m shows that the volume of freshwater lenses will be reduced due to the reduction in the island surface, and in this case the thickness of the lens will be reduced by 5.1%. Considering the simultaneous effect of sea level rise and increasing the net recharge rate by 20%, it can be seen that these two parameters will impact the freshwater lens of the island in opposite directions, and despite the sea level rise, compared to the current state, the island's freshwater lens thickness will be increased by 5.2% [51]. This shows that even if the sea level rises, with recharging the proper amount of freshwater into the island aquifer, not only the thickness of the freshwater lens can be maintained, but also it can be improved. In the case of Kish Island, this issue can be easily met when the proposed recharge system is filled once a year and the recharge rate is increased by 25%.

Finally, the latest scenario is a 1 m increase in sea level and a 15% decrease in net recharge volume, which has the most adverse effect on the island's freshwater lens. Reducing the net recharge rate shrinks the lens and has a synergistic effect with increasing the sea level. Under these conditions, the thickness of the lens will be decreased by 12.4% [51]. In this case, this adverse effect can be compensated by the proposed recharge system filling up only once a year, and even assuming that it is filled twice, the thickness of the freshwater lens can be improved.

Another point to consider is about the amount of water that can be harvested. Assuming that the current condition of water extraction from freshwater lens is stable, it can be thought that by increasing the net recharge rate, it will be possible to allow extraction of more water from the aquifer; as mentioned earlier, assuming the proposed system is filled only once, 25% more water would be available in the aquifer, which would be about

450,000 m^3 per year if considered at the island level. Furthermore, in scenarios where the amount of precipitation decreases or the sea water level rises, it will be possible to maintain the current amount of water extraction by constructing the proposed system.

Another issue to discuss is the water infiltration rate, at the level of the study area and the proposed systems. The location of the recharge systems is determined based on the position of the main channel route, permeability, groundwater depth, and surface features. In general, the results of permeability tests show that the permeability is high near the shoreline (about 5.5×10^{-5} Ls^{-1}) and decreases continuously with distance from it (about 1×10^{-5} Ls^{-1}). On the other hand, the depth of groundwater near the shore is very shallow (about 2 m) and this depth increases with distance from the sea (up to 15 m). As it is shown in Figure 7, considering the conditions required to build a recharge system in the study area, three zones were defined. The red area, which is a narrow strip near the shoreline, although it enjoys a good permeability rate, due to the shallow depth of groundwater, it is not possible to build an efficient recharge system. The green area enjoys both good permeability rate and suitable groundwater depth, which makes the conditions ideal for the construction of a recharge system. The orange area has less permeability rate than others, and the groundwater depth has increased, and therefore recharge systems might not work as efficiently as in the green zone, and they will fulfill their functions at a slower rate.

Figure 7. Permeability zones of the study area [52]: Google Maps, 2022. Kish Island, 1:500. Google Maps (online) Available through: Polytechnic School of Ávila https://www.google.com/maps (accessed 24 April 2022).

According to the infiltration potential of each system, 33 proposed systems were divided into group A and group B. Group A includes 13 recharge systems that will recharge at the rate of 282 Ls^{-1} (67% of the total recharge rate), and group B includes 20 recharge systems that will have a 140 Ls^{-1} recharge rate, i.e., almost twice the number, and half the rate. Therefore, if authorities or decision makers want to prioritize the construction of these recharge systems based on the budget or limited time of construction, it is obvious that the first priority will be with the construction of Group A recharge systems (which are located in green zone) and then the second priority with the construction of Group B recharge systems (which are located in orange zone). It should be noted that apart from infiltration volume during rainfall, which is definitely much higher for Group A systems, in any case both systems will recharge the stored volume to the aquifer and the only difference will be in the time of recharge.

Stormwater infiltration systems are typically expected to drain down within 24 h of a storm, meaning that the infiltration rate should be high enough that no water is left ponding after 24 h [53]. The proposed recharge systems are located next to a stormwater network and preventing floods and providing flood protection is the main responsibility of mentioned stormwater network; yet, the proposed recharge systems are discharged in less than 24 h. Table 4 shows the time required to discharge for each of the recharge systems. In general, Group A recharge systems require between 6 and 10 h to discharge due to the high penetration rate, and Group B systems require between 18 and 23 h due to the lower penetration rate.

Table 4. Duration to infiltrate from full storage to empty storage of proposed recharge systems.

Group A				Group B			
Recharge System	Storage (m^3)	Infiltration Rate (Ls^{-1})	Duration (h.)	Recharge System	Storage (m^3)	Infiltration Rate (Ls^{-1})	Duration (h.)
R21	536.0	15.7	9.5	R1	527.6	7.8	18.8
R22	536.0	23.5	6.3	R2	524.8	7.8	18.7
R23	527.6	23.5	6.2	R3	522.0	6.3	23.0
R24	524.8	23.5	6.2	R4	522.0	6.3	23.0
R25	524.8	23.5	6.2	R5	524.8	6.8	21.4
R26	524.8	23.5	6.2	R6	524.8	7.3	20.0
R27	524.8	23.5	6.2	R7	524.8	7.3	20.0
R28	524.8	23.5	6.2	R8	522.0	7.3	19.9
R29	522.0	23.5	6.2	R9	522.0	7.3	19.9
R30	522.0	23.5	6.2	R10	522.0	6.8	21.3
R31	522.0	23.5	6.2	R11	522.0	6.8	21.3
R32	522.0	15.7	9.2	R12	533.2	6.3	23.5
R33	522.0	15.7	9.2	R13	530.4	6.3	23.4
				R14	527.6	6.8	21.6
				R15	524.8	6.8	21.4
				R16	524.8	6.8	21.4
				R17	524.8	6.8	21.4
				R18	524.8	6.8	21.4
				R19	524.8	6.8	21.4
				R20	530.4	7.8	18.9

In general, it can be said that the sustainability of any society is in direct relation to the sustainability of its components, and certainly water security plays a crucial role in this regard. As the results showed, the proposed system is able to improve the conditions of the study area by increasing the groundwater level for future use, counteracting the seawater intrusion and climate change.

It is also noteworthy that in many urban communities, a large portion of the available water is used by industry, and not being able to support these industrial needs will cause much damage to this sector. The proposed groundwater recharge system is able to artificially recharge aquifers with rainwater in order to supply cheap and quality water to the industry.

In addition, from the general economic point of view, stability is one of the most important factors in attracting and maintaining capital. Establishing balance in water management and reducing the risk of water stress greatly contributes to the sustainability of the existing ecosystem and paves the way for its development and progress.

In terms of habitat and ecology, increasing the groundwater level using the proposed method to make more water available to plants and trees will help the ecosystem to be more stable and sustainable.

In addition to all these benefits that improve living conditions in cities and human societies, human dependence on clean water in terms of household needs and drinking is extremely high. The proposed system provides the community with more, cheaper, and cleaner water by recharging the aquifer, and consequently will reduce water stress and increase the sense of water security in societies.

5. Conclusions

One of the main pillars of development in human societies is the freshwater supply; without having enough renewable freshwater, no development will be sustainable. As human societies have always developed and their population grown rapidly, the consequent increasing water demand must be resolved. Due to the limited amount of freshwater available, groundwater is usually one of the first resources to be used as a replacement for scarcity. Excessive use of groundwater resources will lead to a drop in their level and cause many problems such as soil subsidence, reduced water quality, and seawater intrusion.

Groundwater has been extracted from aquifers over the years in various locations around the world, and either the impacts have become visible in many places or will become so soon; thus, providing a solution to this problem is an immediate necessity. One way to deal with these problems is to recharge groundwater artificially to compensate the lost water and bring balance to aquifers. There are many different ways in this regard, although usually these methods are not very effective in urban environments due to the need for large spaces or applicability in small basins; therefore, in this research a new approach is proposed to implement artificial recharge facilities in cities with high efficiency and without the negative aspects.

In general, the new proposed system, which is called the Groundwater Recharge System (GRS), works by modifying the existing stormwater management network and using it as a collector, supplier, and conveyer of water sources to enter the recharge systems installed in its vicinity and through its length, while their main objective, which is to ensure safety against floods, remains intact. The design and implementation of the mentioned system in the study area showed that even in the worst-case scenario, when this system is filled only once a year, it will be able not only to resolve many of the adverse effects of groundwater overuse, but also will be able to deal with the effects of climate change impacts such as precipitation reduction and rising sea levels. Along with all these advantages, perhaps the most important features of the proposed facility are its cheap and fast construction along with the lack of the need for complex technologies.

The proposed technique is also in direct line with the sixth goal of the United Nations' Sustainable Development Goals (SDGs), clean water and sanitation, which is described as to ensure availability and sustainable management of water and sanitation for all. The mentioned goal has eight targets to achieve by the year 2030. The groundwater recharge system has a positive role in all of them, however, it is in direct line with target 6.6 (protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes) and target 6.a (expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling, and reuse technologies), as the proposed technique uses water harvesting to protect aquifers [54].

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References

1. Wada, Y.; van Beek, L.P.; Van Kempen, C.M.; Reckman, J.W.T.M.; Vasak, S.; Bierkens, M.F. Global depletion of groundwater resources. *Geophys. Res. Lett.* **2010**, *37*, L20402. [CrossRef]
2. Hanasaki, N.; Kanae, S.; Oki, T.; Masuda, K.; Motoya, K.; Shirakawa, N.; Shen, Y.; Tanaka, K. An integrated model for the assessment of global water resources—Part 2: Applications and assessments. *Hydrol. Earth Syst. Sci.* **2008**, *12*, 1027–1037. [CrossRef]
3. Alcamo, J.; Henrichs, T.; Rösch, T. World water in 2025: Global modeling and scenario analysis for the World Commission on Water for the 21st Century. In *Kassel World Water Series*; Center for Environmental Systems Research, University of Kassel: Kassel, Germany, 2000.
4. FAO. *Global Forest Resources Assessment 2010. FAO Forestry Paper 163*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2010.
5. Boretti, A.; Rosa, L. Reassessing the projections of the world water development report. *Npj Clean Water* **2019**, *2*, 1–6. [CrossRef]
6. Wada, Y.; Wisser, D.; Bierkens, M.F. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth Syst. Dynam.* **2014**, *5*, 15–40. [CrossRef]
7. World Bank. *Annual Report 2010*; World Bank: Washington, DC, USA, 2010.
8. Kadam, A.K.; Umrikar, B.N.; Sankhua, R.N. Assessment of recharge potential zones for groundwater development and management using geospatial and MCDA technologies in semi-arid region of Western India. *SN Appl. Sci.* **2020**, *2*, 312. [CrossRef]
9. Rhoades, J.D.; Kandiah, A.; Mashali, A.M. The use of saline waters for crop production. In *FAO Irrigation & Drainage Paper*; FAO: Rome, Italy, 1992.
10. Eurostat. The Dominance of Capital Cities, Urban Europe—Statistics on Cities, Towns and Suburbs. 2016. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Urban_Europe_%E2%80%94_statistics_on_cities,_towns_and_suburbs_%E2%80%94_the_dominance_of_capital_cities&oldid=296362 (accessed on 10 April 2022).
11. EEA (European Environment Agency). Use of Freshwater Resources in Europe. 2018. Available online: https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-3/assessment-4 (accessed on 9 April 2022).
12. WFD (Water Framework Directive). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000. In *Official Journal of the European Communities L 327/1*; WFD: Rome, Italy, 2000.
13. EEA (European Environment Agency). Water in the City. 2019. Available online: https://www.eea.europa.eu/signals/signals-2018-content-list/articles/close-up-2014-water-in (accessed on 19 March 2022).
14. Kadam, A.; Karnewar, A.S.; Umrikar, B.; Sankhua, R.N. Hydrological response-based watershed prioritization in semi-arid, basaltic region of western India using frequency ratio, fuzzy logic and AHP method. Environ. *Dev. Sustain.* **2019**, *21*, 1809–1833. [CrossRef]
15. USGS. Available online: https://www.usgs.gov/special-topics/water-science-school/science/groundwater-decline-and-depletion (accessed on 25 April 2022).
16. CGR (Committee on Groundwater Recharge). *Groundwater Recharge Using Water of Impaired Quality*; National Academy Press: Washington, DC, USA, 1994.
17. Mays, L.; Antoniou, G.P.; Angelakis, A.N. History of water cisterns: Legacies and lessons. *Water* **2013**, *5*, 1916–1940. [CrossRef]
18. Texas Water Development Board. *The Texas Manual on Rainwater Harvesting*, 3rd ed.; Texas Water Development Board: Austin, TX, USA, 2005.
19. Vieira, A.S.; Beal, C.D.; Ghisi, E.; Stewart, R.A. Energy intensity of rainwater harvesting systems: A review. *Renew. Sustain. Energy Rev.* **2014**, *34*, 225–242. [CrossRef]
20. Belmeziti, A.; Olivier, C.; Bernard, D.G. A new methodology for evaluating potential for potable water savings (PPWS) by using rainwater harvesting at the urban level: The case of the municipality of Colombes (Paris region). *Water* **2013**, *5*, 312–326. [CrossRef]
21. Liaw, C.H.; Chiang, Y.C. Dimensionless analysis for designing domestic rainwater harvesting systems at the regional level in northern Taiwan. *Water* **2014**, *6*, 3913–3933. [CrossRef]
22. Campisano, A.; Gnecco, I.; Modica, C.; Palla, A. Designing domestic rainwater harvesting systems under different climatic regimes in Italy. *Water Sci. Technol.* **2013**, *67*, 2511–2518. [CrossRef] [PubMed]
23. Hajani, E.; Rahman, A. Reliability and cost analysis of a rainwater harvesting system in peri-urban regions of greater Sydney, Australia. *Water* **2014**, *6*, 945–960. [CrossRef]
24. Hussain, F.; Hussain, R.; Wu, R.S.; Abbas, T. Rainwater Harvesting Potential and Utilization for Artificial Recharge of Groundwater Using Recharge Wells. *Processes* **2019**, *7*, 623. [CrossRef]

25. Rahman, A.; Keane, J.; Imteaz, M.A. Rainwater harvesting in Greater Sydney: Water savings, reliability and economic benefits. *Resour. Conserv. Recycl.* **2012**, *61*, 16–21. [CrossRef]
26. Ghisi, E.; Tavares, D.F.; Rocha, V.L. Rainwater harvesting in petrol stations in Brasília: Potential for potable water savings and investment feasibility analysis. *Resour. Conserv. Recycl.* **2009**, *54*, 79–85. [CrossRef]
27. Li, X.; Gong, J. Compacted micro-catchments with local earth materials for rainwater harvesting in the semiarid region of China. *J. Hydrol.* **2002**, *257*, 134–144. [CrossRef]
28. Yuan, T.; Fengmin, L.; Puhai, L. Economic analysis of rainwater harvesting and irrigation methods, with an example from China. Agric. *Water Manag.* **2003**, *60*, 21–226. [CrossRef]
29. Sazakli, E.; Alexopoulos, A.; Leotsinidis, M. Rainwater harvesting, quality assessment and utilization in Kefalonia Island, Greece. *Water Res.* **2007**, *41*, 2039–2047. [CrossRef]
30. Goel, A.K.; Kumar, R. Economic analysis of water harvesting in a mountainous watershed in India. Agric. *Water Manag.* **2005**, *71*, 257–266. [CrossRef]
31. Pandey, P.K.; Panda, S.N.; Panigrahi, B. Sizing on-farm reservoirs for crop-fish integration in rain-fed farming systems in Eastern India. *Biosyst. Eng.* **2006**, *93*, 475–489. [CrossRef]
32. Islam, M.M.; Chou, F.F.; Kabir, M.R.; Liaw, C.H. Rainwater: A potential alternative source for scarce safe drinking and arsenic contaminated water in Bangladesh. *Water Resour. Manag.* **2010**, *24*, 3987–4008. [CrossRef]
33. Mohammad, H.R.M.; Bahram, S.; Fereshte, H.F. Assessment of residential rainwater harvesting efficiency for meeting non-potable water demands in three climate conditions. *Resour. Conserv. Recycl.* **2013**, *73*, 86–93. [CrossRef]
34. Fooladman, H.R.; Sepaskhah, A.R. Economic analysis for the production of four grape cultivars using micro-catchment water harvesting systems in Iran. *J. Arid. Environ.* **2004**, *58*, 525–533. [CrossRef]
35. Ahmed, A.; Farooq, A. Study of rainwater harvesting potential in an industrial area using stormwater management model (SWMM V 5.0)—A case study of Quaid-E-Azam Apparel Park, Sheikhupura, Punjab, Pakistan. *Int. J. Environ. Eng.* **2018**, *9*, 185–198. [CrossRef]
36. Siddiqui, R.; Siddiqui, S. Assessing the Rooftop Rainwater Harvesting Potential in Urban Residential Areas of Pakistan: A Case Study of Model Town, Lahore, Pakistan. *Int. J. Econ. Environ. Geol.* **2018**, *9*, 11–19.
37. Hassan, I. Rainwater Harvesting-an alternative water supply in the Future for Pakistan. *J. Biodivers. Environ. Sci.* **2016**, *8*, 213–222.
38. Song, J.; Han, M.; Kim, T. Rainwater harvesting as a sustainable water supply option in Banda Aceh. *Desalination* **2009**, *248*, 233–240. [CrossRef]
39. Macomber, P.S.H. *Guidelines on Rainwater Catchment Systems for Hawaii*; College of Tropical Agriculture and Human Resources (CTAHR), University of Hawai'i at Manoa: Honolulu, HI, USA, 2010; p. RM-12.
40. Black, J.; Malesu, M.; Oduor, A.; Cherogony, K.; Nyabenge, M. *Rainwater Harvesting Inventory of Kenya an Overview of Techniques, Sustainability Factors, and Stakeholders*; World Agroforestry Centre (ICRAF): Nairobi, Kenya, 2012.
41. Reddy, G.S.; Sandhya, S.; Hanumanthu, R. The Need of Artificial Recharge Techniques for Sustainable Development of Ground Water Resources. *Int. J. Geol. Earth Sci.* **2019**, *5*, 131–145. [CrossRef]
42. Ministry of Water Resources. *Guide on Artificial Recharge to Groundwater*; Ministry of Water Resources: Delhi, India, 2000.
43. Kish Free Zone Organization. Available online: https://portal.kish.ir/en (accessed on 24 April 2022).
44. Polytechnic School of Ávila. Google Maps, 2022. Kish Island, 1:33,333 and 1:500. Google Maps [online]. Available online: https://www.google.com/maps (accessed on 24 April 2022).
45. Ketabchi, H.; Ataie-Ashtiani, B. Evolutionary algorithms for the optimal management of coastal groundwater: A comparative study toward future challenges. *J. Hyd.* **2015**, *520*, 193–213. [CrossRef]
46. Khoshdooz-Masooleh, N.; Babazadeh, H.; Tabatabaei, H.; Naderi, M. Modifying DRASTIC model to determine groundwater vulnerability in a coastal region. *J. Water Soil Resour. Conserv.* **2013**, *1*, 19–31. Available online: https://www.sid.ir/fa/journal/ViewPaper.aspx?id=218711 (accessed on 18 March 2022).
47. Ketabchi, H.; Ataie-Ashtiani, B.; Rajabi, M. Providing practical solutions for optimal utilization of groundwater resources of small islands (Case study of Kish Island). In Proceedings of the 12th Iranian Hydraulic Conference, Karaj, Iran, 29 October 2013; Available online: https://civilica.com/doc/379263 (accessed on 10 April 2022).
48. Atashkhar, F.; Shirani, M.; Tabatabaei, H. Relationship between some qualitative and quantitative parameters of groundwater resources in Kish Island. In Proceedings of the 1st National Conference on Coastal Lands, 8 December 2010; *Water Resour. Manag.* Available online: https://civilica.com/doc/105771 (accessed on 8 March 2022).
49. Ataie-Ashtiani, B.; Rajabi, M.M.; Ketabchi, H. Inverse modeling for freshwater lens in small islands: Kish Island, Persian Gulf. *Hydrol. Process* **2013**, *27*, 2759–2773. [CrossRef]
50. Ketabchi, H.; Ataie-Ashtiani, B. Development of combined ant colony optimization algorithm and numerical simulation for optimal management of coastal aquifers. *IR-WRR* **2010**, *7*, 1–12.
51. Mahmoodzadeh, D.; Ketabchi, H.; Ataie-Ashtiani, B. Optimized Management of Groundwater Resources in Kish Island: A Sensitivity Analysis of Optimal Strategies in Response to Environmental Changes. *Wat. Wastewater J.* **2015**, *2*, 61–70. Available online: http://www.wwjournal.ir/article_12986.html (accessed on 17 March 2022).
52. Polytechnic School of Ávila. Google Maps, 2022. Kish Island, 1:500. Google Maps [online]. Available online: https://www.google.com/maps (accessed on 24 April 2022).

53. EPA (U.S. Environmental Protection Agency). Evaluation and Optimization of Bioretention Design for Nitrogen and Phosphorus Removal. 2013. Available online: https://www3.epa.gov/region1/npdes/stormwater/research/epa-final-report-filter-study.pdf (accessed on 20 March 2022).
54. Department of Economic and Social Affairs, Sustainable Development. Available online: https://sdgs.un.org/goals/goal6 (accessed on 7 May 2022).

Capítulo 4 "ARTÍCULO 3"

4.1. Objetivo:

Rainfall is the climate variable that may cause the most widespread social and economic impacts to society. Earth's climate is increasingly changing, and its impacts can be related to drought or floods which affects numerous productive activities. Additionally, during the past few decades, it has become increasingly clear that old hydrological patterns are changing which is causing climate variability and the hydrological processes that are related to it to increase globally. In order to evaluate the potential effects of climate change and variability, numerous research on the trend of rainfall on various regional and temporal scales have been carried out. In developing regions, variations in rainfall have a negative impact on crop productivity and impose harsh climatic conditions. Studies that are very focused on climatic variables, such as variability in rainfall and temperature, are essential, especially in places that are mostly based on rainfall resources, But, because rain is dynamic in nature, it is very difficult to anticipate with any degree of accuracy. Therefore, hybrid approaches should be used to solve the shortcomings of rainfall forecasting because of the periodic nature and non-linear properties of rainfall. In order to forecast seasonal rainfall, some research has suggested using artificial neural networks (ANN), fuzzy logic, neural networks, and autoregressive integrated moving averages (ARIMA). It has also become a relevant issue in recent decades, especially when considering the associated extreme events.

The objectives of the present case study are to (1) determine the suitable value of IETD for rainfall events in a representative study-case (2) summarize the characteristics of rainfall events (3) identify the homogeneous rainfall events and (4) investigate the characteristics of the rainfall events found in each cluster (5) determine and verify the shape (geometry) of precipitation hyetographs based on the clusters design.

The Above Paragraphs In Spanish:

Las precipitaciones son la variable climática que puede provocar los impactos sociales y económicos más generalizados en la sociedad. El clima de la Tierra es cada vez más cambiante y sus impactos pueden estar relacionados con sequías o inundaciones que afectan a numerosas actividades productivas. Además, durante las últimas décadas, se ha vuelto cada vez más claro que los viejos patrones hidrológicos están cambiando, lo que está provocando que la variabilidad climática y los procesos hidrológicos relacionados con ella aumenten a nivel mundial . Para evaluar los efectos potenciales del cambio y la variabilidad climática se han llevado a cabo numerosas investigaciones sobre la tendencia de las precipitaciones en diversas escalas regionales y temporales. En las regiones en desarrollo, las variaciones en las precipitaciones tienen un impacto negativo en la productividad de los cultivos e imponen condiciones climáticas duras. Los estudios que están muy centrados en variables climáticas, como la variabilidad de las precipitaciones y la temperatura, son esenciales, especialmente en lugares que se basan principalmente en recursos de lluvia, pero, debido a que la lluvia es de naturaleza dinámica, es muy difícil anticiparla con algún grado de exactitud. Por lo tanto, se deben utilizar enfoques híbridos para resolver las deficiencias del pronóstico de precipitaciones debido a la naturaleza periódica y las propiedades no lineales de las precipitaciones. Para pronosticar las precipitaciones estacionales, algunas investigaciones han sugerido el uso de redes neuronales artificiales (ANN), lógica difusa, redes neuronales y promedios móviles integrados autorregresivos (ARIMA). También se ha convertido en un tema relevante en las últimas décadas, especialmente si se consideran los eventos extremos asociados.

Los objetivos del presente estudio de caso son (1) determinar el valor adecuado de IETD para eventos de lluvia en un caso de estudio representativo (2) resumir las características de los eventos de lluvia (3) identificar los eventos de lluvia homogéneos y (4) investigar la Las características de los eventos de lluvia encontrados en cada conglomerado (5) determinan y verifican la forma (geometría) de los hietogramas de precipitación con base en el diseño de los conglomerados.

4.2. Metodología:

This research shows an innovative method for the characterization and design of regional hyetographs with the following steps. First, due to the large number of rainfall records, a grouping of rainfall events is obtained by means of correlogram analysis. Then, cluster analysis is applied to group the events into specific clusters using the silhouette index. Based on the data resulting from cluster analysis (hierarchical), the hyetograph is built considering the maximum intensity found in each of the analyzed clusters. And finally, a characterization of the clusters found was carried out.

Statistical analysis of the 14-year hourly rainfall data recorded from 2008 to 2022 was conducted. In this sense, 252,755 hourly 30-minute data records were collected.

The Above Paragraphs In Spanish:

Esta investigación muestra un método innovador para la caracterización y diseño de hietogramas regionales con los siguientes pasos. En primer lugar, debido a la gran cantidad de registros de lluvia, se obtiene una agrupación de eventos de lluvia mediante análisis de correlograma. Luego, se aplica el análisis de conglomerados para agrupar los eventos en conglomerados específicos utilizando el índice de silueta. A partir de los datos resultantes del análisis de conglomerados (jerárquico), se construye el hietograma considerando la intensidad máxima encontrada en cada uno de los conglomerados analizados. Y finalmente se realizó una caracterización de los clusters encontrados.

Se realizó un análisis estadístico de los datos de precipitaciones por hora de 14 años registrados entre 2008 y 2022. En este sentido, se recogieron 252.755 registros de datos horarios de 30 minutos.

4.3. resultados:

In conclusion, the way of identifying clusters based on the previous methodological approach has allowed to robustly differentiate the three main of hyetographs that represents the three main types of rainfall. In more detail, the results obtained in this study identify three well-differentiated clusters to obtain a multivariate characterization of the rainfall: the first group consisted of strong intensity, moderately long-lasting events with the peak intensity centered in the first quarter, just before the event started. The second group was characterized by occurrences of long duration, moderate intensity, presumably related with a major precipitation front sustained throughout time, while the third group was characterized by events of extended duration till the maximum peak is reached with moderate intensity and duration. Hyetoclust becomes a general tool that can be applied to any meteorological/hydrological context. This new tool can assist on the prediction of events (ordinary and extremal) and the effective integration to Early Warning Systems. Through Hyetoclust application it is expected to reduce the amount of losses and damage associated to extreme hydrological phenomena.

The Above Paragraphs In Spanish:

En conclusión, la forma de identificar clusters basada en el enfoque metodológico anterior ha permitido diferenciar robustamente los tres principales hietogramas que representan los tres principales tipos de lluvia. Más detalladamente, los resultados obtenidos en este estudio identifican tres grupos bien diferenciados para obtener una caracterización multivariada de las precipitaciones: el primer grupo estuvo formado por eventos de fuerte intensidad y duración moderada, con el pico de intensidad centrado en el primer trimestre, justo antes el evento comenzó. El segundo grupo se caracterizó por eventos de larga duración, intensidad moderada, presumiblemente relacionados con un frente importante de precipitación sostenido a lo largo del tiempo, mientras que el tercer grupo se caracterizó por eventos de duración extendida hasta alcanzar el pico máximo con intensidad y duración moderada. Hyetoclust se convierte en una herramienta general que se puede aplicar a cualquier contexto meteorológico/hidrológico. Esta nueva herramienta puede ayudar en la predicción de eventos (ordinarios y extremos) y la integración efectiva a los Sistemas de Alerta Temprana. Mediante la aplicación de Hyetoclust se espera reducir la cantidad de pérdidas y daños asociados a fenómenos hidrológicos extremos.

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Research papers

HyetoClust method: Hyetograph design through cluster analysis

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ABSTRACT

Given the increasing non-stationarity of hydrological processes largely due to Climate Change (CC), it is essential to create more accurate methods. The inherent spatiotemporal variability of hydrological processes reaches its maximum when it comes to rainfall process. Rainfall is typically divided up into events in hydrological studies, but this does not acquire the necessary analytical importance. The objective of the research is dual. First, to generate a robust method for the identification and characterization of homogeneous rainfall events, largely based on the geometrical analysis of clustered hyetographs. Second, the generation of more accurate hyetographs. The study was built on the idea of Inter-Event Time Definition (IETD) and thresholds for rainfall depth, duration, and intensity. The rainfalls were grouped due to the similarity of features as: duration, volume, intensity, time maximum pick and interevent using hierarchical cluster analysis. The study area is placed in the Muñogalindo station located in the province of Avila (Spain) and characterized by an altitude above 1,132 m. Hierarchical cluster analysis showed to be particularly effective for selecting precipitation based on hyetograph shape. Cluster method strongly revealed the identification of three rainfall everts groups. HyetoClust is intended to provide the scientific and technical community with a new tool for characterization of rainfall everts and the generation of more accurate hyetographs for supporting hydrological prediction.

1. Introduction

Rainfall is the climate variable that may cause the most widespread social and economic impacts to society (Choo et al., 2020). Earth's climate is increasingly changing and its impacts can be related to drought or floods (Lyra et al., 2014) which affects numerous productive activities. Additionally, during the past few decades, it has become increasingly clear that old hydrological patterns are changing which is causing climate variability and the hydrological processes that are related to it to increase globally (Molina and Zazo, 2018). In order to evaluate the potential effects of climate change and variability, numerous research on the trend of rainfall on various regional and temporal scales have been carried out (Abolverdi et al., 2016; Sa'adi et al., 2019). In developing regions, variations in rainfall have a negative impact on crop productivity and impose harsh climatic conditions. Studies that are very focused on climatic variables, such as variability in rainfall and temperature, are essential, especially in places that are mostly based on rainfall resources, But, because rain is dynamic in nature, it is very difficult to anticipate with any degree of accuracy (Fahad et al., 2023). Therefore, hybrid approaches should be used to solve the shortcomings of rainfall forecasting because of the periodic nature and non-linear properties of rainfall. In order to forecast seasonal rainfall, some research has suggested using artificial neural networks (ANN), fuzzy logic, neural networks, and autoregressive integrated moving averages (ARIMA) (Thakur et al., 2021; Wong et al., 2003). It has also become a relevant issue in recent decades, especially when considering the associated extreme events (Benabdelouahab et al., 2020).

According to O'Gorman (2015) a warming climate will result in more intense precipitation extremes. Extreme phenomena are of interest in all disciplines. Some of them, such as strong storms, flooding or heat waves cause more extensive damage and impacts on people, infrastructure, and ecosystems. Because they have the potential to do considerable harm and have an impact on environmental, social, and technological systems, extreme events have gained the attention of

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scientists and management in recent years. The definition of an extreme event varies among studies and fields, where it is typically used interchangeably with its repercussions (McPhillips et al., 2018). In Hydrology the term extreme event referred to those events that have values exceeding a predetermined threshold. To find the extreme levels, a threshold should be carefully determined (Hamitouche and Molina, 2022a). To establish a threshold for analyzing and modeling severe occurrences, a variety of techniques have been explored (McPhillips et al., 2018). Understanding the processes that cause hydrological and hydraulic extremes is essential to reducing their negative effects on society. One of the key tools in this quest for information is hydrological modeling, but it has limitations. For so, a thorough examination of how the structure of hydrological models affects the frequency and timing of extreme rainfall-runoff events is required (Molina et al., 2022). For this reason, rainfall variability in space and time has been researched using different stochastic and statistical method, such as principal component analysis, standard regression models and non-hierarchical classification (Chen et al., 2021; Sahu et al., 2022). According to Hamitouche and Molina's (Hamitouche and Molina, 2022b) review about artificial intelligence methods for high-flow extremes prediction artificial neural networks, support vector machine, wavelets, and Bayesian methods consistently perform the best for high-flow extremes prediction at all time scales. However, rainfall has several disadvantages regarding its treatment. In this sense, it requires accurate conditions for real-time precipitation data, often difficult to obtain. Extreme rainfall for a specific return period is necessary to build or develop various hydraulic projects. For example, for the design of drainage systems in urban catchments, which are typically characterized by fast reaction, hourly rainfall events or shorter are particularly required (Aronica and Freni, 2005). Also, it is necessary to precisely represent rainfall key parameters to be able to identify events. This largely depends on the criteria adopted for the identification and on the availability of rainfall records (Iadanza et al., 2016). According to Lima et al. (Lima et al., 2021) when taking into account long-term series and statistical inferences of anomalies, extreme rainfall occurrences are defined as records throughout a time period (daily, seasonal, annual) that are significantly greater than the average values for the region. It is important to specify the probability of occurrence when taking into account extreme climate events, which is typically expressed by their recurrence intervals (Chen and Singh, 2018).

For hydrological and climatic studies, it is crucial to understand the rain features. For this purpose, rainfall-runoff modelling can be done in two ways, continuous or event-driven (Tokar, 1996). Studies that cover real precipitation to hydrological or biological systems typically categorize rainfall into events. Due to the very erratic rainfall distribution across time, defining what constitutes a rain event is not an easy task. For assessing the features of extreme events that set off the aforementioned physical processes, sub-daily rainfall data are required (Lewis et al., 2019). Many hydrological applications require sub-daily rainfall data, yet in areas with poor gauges around the world, ground-based data availability is still a problem. In order to estimate sub-daily rainfall data globally, satellite remote sensing missions like the Global Precipitation Measurement (GPM) mission have proved crucial (Freitas et al., 2020). Hence, breaking down the rainfall into events is crucial for hydrological applications to have a better knowledge of these processes. For both surface and subsurface hydrology, rainfall partitioning at the soil-atmosphere interface is crucial. It affects several significant hydrologic events, including runoff generation, aquifer recharge, and the movement of contaminants in surface waters and the vadose zone (Morbidelli et al., 2018).

On the other side, when extreme events are affected by both dynamical as mesoscale and physiographic as land cover, lakes, terrain factors, the identification of homogeneous zones of extreme occurrence is crucial (Knerr et al., 2020). According to Ragetteli (2017), semiarid and arid regions are characterized by intensity rainfall very high, and the rainfall duration is low.

An example of characterization of rainfall using probability distributions functions and clustering analysis was given by Lima et al. (Lima et al., 2021) who presented an empirical analysis of time series data of annual maximum daily rainfall which obtained from stations in the state of Rio de Janeiro. Their results showed five regions with homogeneous pattern of extreme rainfall. On the other hand, to make rainfall design easier, which typically necessitates having a solid understanding of the temporal patterns of rainstorm events, it is required to analyze the temporal rainfall pattern (Jun et al., 2021). There are several methods for delimitating independent rainfall events, such as autocorrelation analysis (Grace and Eagleson, 1967), a minimum inter-event time dry period (Dunkerley, 2008), the exponential method (Restrepo-Posada and Eagleson, 1982) or Inter-event Time Definition (IETD) (Howard, 1976). It is challenging to determine the beginning and conclusion of events because of this intermittency, which also has an impact on event characteristics. The delineation of rain events in the literature is different and is mostly dependent on the research topic and the data's time resolution (Molina-Sanchis et al., 2016). The average intensity, peak intensity, number peak, volume, duration and inter-event time (IET), velocity and their spatial and temporal variability are some of the variables that used in the analysis and design of hydraulic systems (Hong et al., 2018; Joo et al., 2013). Also, the identification of homogeneous rainfall events is essential when natural catastrophes that are brought on by heavy rainfall can have a variety of negative effects on civilization (da Silva et al., 2020). Clustering analysis based on cumulative hierarchical algorithms, has been used in various parts of the world, including Brazil (Lima et al., 2021), Switzerland (Barton et al., 2016) or France (Knerr et al., 2020).

In general, rainfall depth-duration-frequency (DDF) or intensity–duration–frequency (IDF) curves are used to estimate design rainfall magnitude in the context of Civil Engineering. Theses have the advantageous property of being analytical relationships capable of providing a design rainfall intensity or depth for an assigned duration and return period (Gioia et al., 2021). Also, synthetic hyetographs are used to determine the temporal patterns of design rainfall under various combinations of frequencies and durations. Hydrological analyses typically presume that it is necessary to take into account the temporal variability of point rainfall intensity, which is typically represented graphically by hyetographs (Chimene and Campos, 2020; Wartalska et al., 2020). The rainfall hydrograph is essential for watershed hydrology in general and managing rainfall water.

Wartalska et al. (2020) examined the local precipitation hyetograph shapes and confirmed the reference hyetograph shapes used for designing and simulating the functioning of drainage systems in Poland using Ward and k-means methods. And recently Mikołajewski et al. (2022) in a study also carried out in Poland, used the cluster analysis methodology at an urban precipitation field scale.

The objectives of the present case study are to (1) determine the suitable value of IETD for rainfall events in a representative study-case (2) summarize the characteristics of rainfall events (3) identify the homogeneous rainfall events and (4) investigate the characteristics of the rainfall events found in each cluster (5) determine and verify the shape (geometry) of precipitation hyetographs based on the clusters design.

The research novelty is largely based on the fact that rainfall event represents the analytical core. The more precise the event is defined (pre-process), the more accurate will be the prediction (outcome). Consequently, this new method better reproduces and adapts to the current increasing hydrological variability, which is even more evident in rainfall processes.

The structure of the paper is described as follows: first section covers the paper introduction where a rich state of the art is provided, mainly on rainfall analytical techniques. This section also outlines the main research goals. Second section describes the study area, the data input, which is largely based on precipitation data records, and provides the methods to assess homogeneous rainfall classes. Third section shows the results obtained from this research and, finally, main conclusions and discussion are given in Section 4.

2. Materials and methods

2.1. Study area

The selected case study is the Muñogalindo station, located at Upper Adaja river basin headwaters, which is part of the Cega-Eresma-Adaja exploitation system of the Duero Hydrographic Demarcation (Fig. 1). The basin covers 763 km^2 and a perimeter of 200 km (40°36′09″ to 4°53′42″), with the Muñogalindo station located 20 km upstream from the city of Avila (Spain). Due to its geographic location, Ávila experiences a temperate Mediterranean climate (Köppen classification: Csb), which is bordered by a cold semi-arid environment and features warm summers and cold winters with snowfall (BSk). The coldest month is January, with an average temperature of 3.0 °C (37 °F), while the hottest month is July, with an average temperature of 20.6 °C (69 °F). The typical yearly rainfall is 416 mm (16.38 in). It appears to be in a rain shadow of the northern mountain ranges of the Central System (Sierra de Ávila) since the annual rainfall is lower than in the southern ranges of the Central System. Due to its high altitude (1,132 m above sea level) Ávila has the lowest winter temperatures among the provincial capital cities of Spain.

2.2. Methods

2.2.1. General approach

According to Restrepo-Posada and Eagleson (1982) rainfall tends to arrive in clusters. On the one hand, some approximate criterions have been proposed for the independent rainfall events and arbitrary separation. Grace and Eagleson (1967) and Sariahmed and Kisiel (1968) chose the storm depth for this purpose and other investigators used autocorrelation and rank correlation coefficients-based procedures. Restrero-Posada and Eagleson (1982) proposed a criterion in parameter estimation for Poisson models of annual rainfall frequency in an arid climate and they used the exponentiality of the time between storms as a condition for the statistical independence of storm arrivals. Therefore, the definition of an independent rainfall event has not been agreed upon by hydrologists. On the other hand, separate independent events should be characterized. The prediction of hydrological extremes recognizes both qualitative and quantitative applications. One of the qualitative predictions is risk assessment, and one of the quantitative forecasts is rainfall-runoff. There are several methods to characterize rainfall. For example, Hamitouche and Molina (2022a) with the objective of characterization extreme high-flow events in the Upper Andarax watershed in SE Spain adopted an event-based Bayesian Causal Modelling.

2.2.2. Multivariate analysis for event type identification based on rainfall characteristics

Multivariate statistical techniques including principle component analysis (PCA), factor analysis (FA), and numerous cluster methods have all been highlighted as multivariate techniques that are effective and efficient for classifying meteorological data, such as rainfall (Mrad et al., 2020). Several studies have employed different variables, such as daily precipitation or spatiotemporal data, to find hydrologically homogeneous zones for precipitation. Wang et al. (2017) studied the dependence structure of one-day and multi-day rainfall using copulas and Nazeri Tahroudi et al. (2022) applied a method based on the conditional density of vine cases to drought the rainfall deficiency. Brito et al. (Brito et al., 2017) analized spatial and temporal patterns of rainfall using a linear regression model and cluster analysis in the state of Rio de Janeiro (Brazil). Santos et al. (2019) used hierarchical clustering to classify the sites into different groups with similar trends in Paraíba state. Mrad et al. (2020) applied PCA and cluster analysis (CA) techniques to analized the variability of annual rainfall changes and identification of homogeneous regions in the north-eastern region of Algeria. The annual standardized precipitation index (SPI) based on multivariate analysis has been applied in the identification of rainfall in several recent investigation studies in the Barbate River basin (S. Iberian Peninsula) and in the State of Alagoas (Northeast Brazil) (Costa et al., 2021; Vélez-Nicolás et al., 2022).

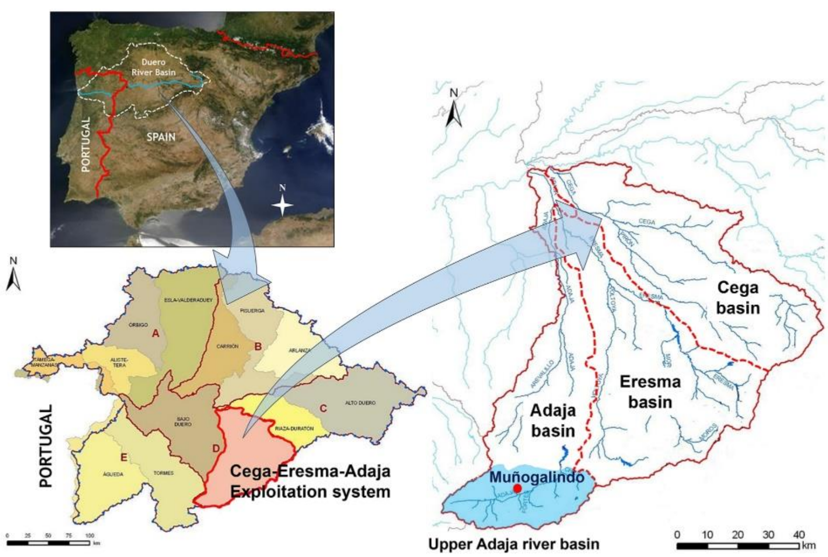

Fig. 1. Case study situation and location of the Muñogalindo station at the Upper Adaja river basin.

2.3. Applied methodology

2.3.1. Overall methodological description

This research shows an innovative method for the characterization and design of regional hyetographs with the following steps. First, due to the large number of rainfall records, a grouping of rainfall events is obtained by means of correlogram analysis. Then, cluster analysis is applied to group the events into specific clusters using the silhouette index. Based on the data resulting from cluster analysis (hierarchical), the hyetograph is built considering the maximum intensity found in each of the analyzed clusters. And finally, a characterization of the clusters found was carried out.

Statistical analysis of the 14-year hourly rainfall data recorded from 2008 to 2022 was conducted. In this sense, 252,755 hourly 30-minute data records were collected. The methodology followed in the study is summarized in Fig. 2.

2.3.2. Identification of independent rainfall events

The continuous historical rainfall series was separated into individual precipitation events using an Interevent Time Definition (IETD) estimation. The IETD defines a minimum dry period between independent rainfall events as a criterion for grouping rainfall events. The precipitation record contains a series of precipitation pulses over time. The minimum inter-event time between consecutive rain pulses (i.e. the definition of time to event, IETD) was used to extract a single storm event from a record of continuous rain events (Adams and Papa, 2000). In case of the drought period between events is longer than the IETD, the storm immediately preceding and the storm immediately following are considered separate events. On the other hand, if the time without precipitation is less than the reported IETD, multiple events were combined into a single one whose duration is equal to the sum of the durations of the two storms plus the drought period itself between the events.

To separate out independent rainfall events from continual precipitation, the IETD needs to be defined initially. The IETD was developed based on the correlation between observed data and temporal proximity using an autocorrelation analysis. The autocorrelation coefficient indicates the correlation of data at a given point in time with data at an earlier point in time. It uses the lag time as the IETD, which is sufficient to isolate independent rainfall events statistically within a specified level of significance meaning that the coefficient of autocorrelation approaches zero (Joo et al., 2013; Adams and Papa 2000). Therefore, it is not based on the statistical independence of rainfall events, but on rainfall pulses. The autocorrelation coefficient ρ_t for a lag time t is computed as:

$$\rho_t = \frac{\sum_{i=1}^{N-t}(Y_i - \overline{Y})(Y_{i+t} - \overline{Y})}{\sum_{i=1}^{N}(Y_i - \overline{Y})^2}$$

where Y_i is the sample of observations at time i, and $\overline{Y}$ is the sample mean of N samples.

2.3.3. Clustering analysis

Cluster analysis was used to identify groups of rainfall with similar physical characteristics using the following variables: volume, intensity, duration and time maximum peak.

The aim of cluster analysis is to find groups rainfall where the events in a cluster have very small differences in terms of their statistical properties.

It is an unsupervised analysis that divides data into similar, overlapping, or non-overlapping groups. The advantage of clustering algorithms is that they generally do not assume any statistical distribution for the input data. A common method to identify groups in a dataset is Ward's hierarchical method (Ward, 1963), considering the squared Euclidean distances to define events with similar rainfall. The distance, d_e, is defined as:

$$d_e = \left[\sum_{i=1}^{n} P_{p,i} - P_{k,i}\right]^{0.5}$$

where d_e is the Euclidian distance, and $P_{p,i}$ and $P_{k,i}$ are the quantitative variables i from elements p and k, respectively.

In addition, the within-group sum of squares of a group is defined as the sum of the distance between all objects in the group and their gravity centre, which is expressed by equation:

$$WtGSS_c = \sum_{i=1}^{n_c} d_e^2(x_{ci} - \overline{x_c})$$

where: n_c and $\overline{x_c}$ are the size and centroid of cluster c.

The silhouette index is utilized because the Ward method does not specify the ideal number of clusters that should be produced. The data were normalized because a variable with different units usually affects the clustering results.

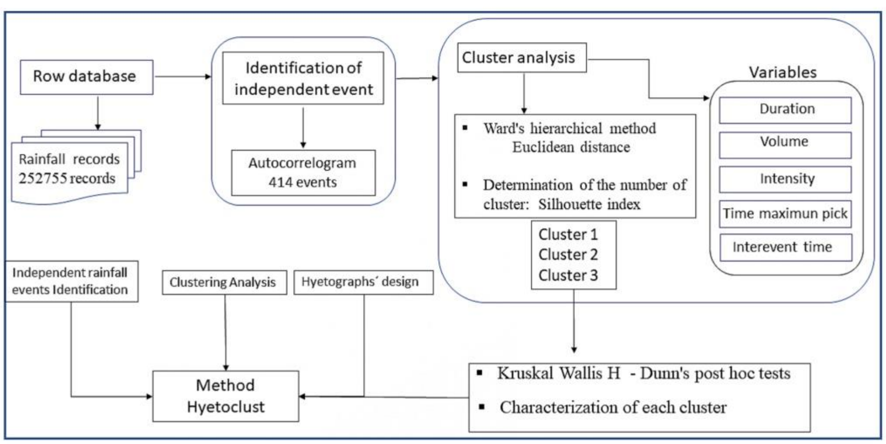

Fig. 2. Research methodology flow chart of this study.

2.3.3.1. Clusterś characterization. The application of a clustering methodology requires the definition of features that can be used to characterize the rain events. Clusters were characterized for typical characteristics (volume, duration, intensity, total depth, interevent time, time maximum peak, maximum peak, relative peak and season).

The quantitative variables are described as mean ± standard deviation. Kruskal Wallis H test was used to identify significant differences between cluster and Dunn's post hoc tests (Dunn, 1964). Chi-squared test was applied to analyse the association of independent qualitative variable among subgroups. Threshold for significance was set at $p \leq 0.05$.

2.3.3.2. Defining features to characterize rain events. Several rainfall characteristics, over the time series were calculated in order to better understand the rainfall phenomena that primarily define the clusters, such as: Event **volume** is defined according to the IETD as the sum of the precipitation per hour reported for a separate event, and precipitation **duration** is the period from the beginning to the end of a precipitation event. Average event **intensity** can be calculated by dividing event volume by duration. **Total depth** is the amount of water that falls per square meter. **Interevent time** is the rain-free interval is that the time between the end point of the previous rain event and the start point of the next. **Time maximum peak** rainfall is the hours from the start of the event until the highest peak. **Maximum peak** is the average maximum intensity over the years 2008–2022 and **relative peak** is defined as the average maximum intensity in each event.

2.3.4. Hyetographś design

This starts with an analysis of similarity features of rainfall hyetographś shapes for the designated clusters, considering the duration and maximum intensity. Since time is a continuous variable, it is considered to group its values in intervals of the same duration (*d*) (temporal range) for each cluster. Consequently, the intervals are established as follows: [t_min, t_min + d], (t_min + d, t_min + 2d],...,(t_min + nd, t_max), where *n* is the number of intervals, t_min and t_max are defined as the minimum/maximum value respectively of the time variable.

For each of the previous intervals, the value for the maximum rainfall intensity is taken (*I_max*). The previous data is represented graphically as a hyetograph in which the intervals are located on the abscissa axis and the maximum intensities for each of them on the ordinate axis.

3. Results

3.1. IETD determination

An analysis based on an autocorrelation method has been used to determine the IETD which it is a standard for identifying an individual event from a continuous rainfall record and it is decided by whether or not there is a connection between nearby events. The autocorrelogram represents a plot of autocorrelation coefficient ρ_t with respect to the lag autocorrelogram indicated that the autocorrelation coefficient is close to zero at approximately 23.5 hrs. (Fig. 3). However, the shape of the autocorrelation graph indicates that this process has an asymptotic behaviour to X Axe from approximately 2.5 h.

3.2. Statistics of precipitation events derived by application of IETD

Based on the IETD technique, total 414 rain events were found within a period of fourteen years. Descriptive statistics of rainfall characteristics are shown in Table 1. Average rainfall duration of 29.51 hrs., intensity of 0.61 mm/hr, and total depth of 7.76 mm were obtained. The interevent time, which is a time frame without rain, can be compared to the typical dry time preceding a storm. The average interevent time of 273.78 hrs were found from these rainfall data.

The duration of precipitation ranged from 0.5 to 198.50 h. The amount of precipitation also ranged from 0.60 to 77.29 mm during the entire period. Precipitation cases with a duration of one hour had the highest frequency with 4.1% (17 times), and a duration of less than one hour was next with 2,7% (11 times). Overall, precipitation events with a duration of<12 h occurred a total of 146 times, and this accounted for 35.3% of the total. Therefore, it should be noted that large duration precipitation events were much more prevalent in Muñogalindo. The amount of precipitation<10 mm had a proportion of 73.9% (306 times) during the 14-year period.

3.3. Clustering analysis

For the work purpose, a detailed examination of the similarities

Table 1
Descriptive statistics of average rainfall data.

	Rainfall duration (hr)	Total rainfall depth (mm)	Rainfall intensity (mm/hr)	Interevent time (hr)
Minimum Value	0.50	0.60	0.2	24.00
Maximum Value	198.50	77.29	11.60	2877.00
Mean Value	29.51	7.76	0.61	273.78
Standar Deviation	29.70	8.29	1.12	372.07

*414 events.

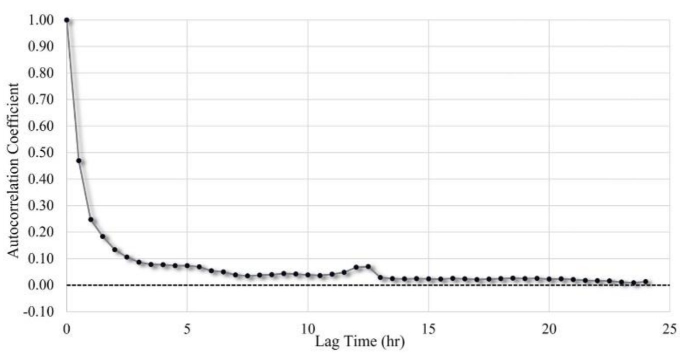

Fig. 3. Autocorrelogram for determining IETD.

between rainfall hyetograph shapes in groups of their duration is done, considering the maximum rainfall intensity. To separate the events in the population under study into homogeneous related subsets, a cluster analysis was first applied. The determination of the optimum number of clusters k = 3 was followed by the hierarchical clustering process. Cluster analysis was done using the Ward method with the following rainfall parameters: duration, volume, intensity, hours from the start of the event until the highest peak and interevent time. Ward method is a hierarchical clustering that uses the increase in the total sum of squares within the cluster as a result of joining clusters. The average value of the silhouette index, $\overline{S}$, was calculated for 2–10 clusters. Based on the silhouette index, the optimum number of clusters for storm events is three.

3.3.1. *Clusterś characterisation*

To characterize the groups of independent events it has been considered as illustrated in Fig. 4, that if the time increment between two events is greater than the IETD they are two separate events. If the time between events is less than or equal to the IETD, it is the same event.

Table 2 shows a general description of the clusters according to the selected variables.

Cluster 1 consists of 176 events and includes the largest number of events. In this cluster, there was a high average rainfall intensity with a value of 0.91 mm/hr and SD of 1.58. Also, it has the highest average value of the interevent time. The average and the standard deviation of interevent time is of 398.11hr and 497.38 respectively.

Cluster 2 consists of 136 events (42.5% of the events). This group had the highest duration overall at 58.52 hrs (SD = 32.67), volume (mean = 58.52 mm, SD = 32.67), time maximum peak with a mean value of the 7.38 hrs and SD equal to 7.72 and, it presents top average event intensity (mean = 2.34 mm/h, SD = 2.48). The average and the standard deviation of interevent time is of 157.73 hr (SD = 163.52).

Cluster 3 represents 24.64% (n = 102) of the events. This clusters reflects the highest number of relative peaks (mean = 21.53, SD = 7.52). The average of interevent time is 215.18 hrs.

Kruskal-Wallis ANOVA confirmed distinct differences between the clusters based on characteristics rainfalls. The results of the Chi-Square statistical test of independence show a calculated p-value > 0.05. This reveals the nonexistence of a statistically significant association and independence between clusters and season.

Table 2
Characteristics of events according to characteristics rainfalls by clusters.

	Cluster 1 n = 176	Cluster 2 n = 136	Cluster 3 n = 102	p value
	Mean ± SD	Mean ± SD	Mean ± SD	
Intensity[a,b]	0.91 ± 1.58	0.37 ± 0.44	0.43 ± 0.56	<0.001
Duration[a,b,c] base	13.03 ± 13.51	58.52 ± 32.67	19.26 ± 12.21	<0.001
Volumen[a,c]	4.39 ± 3.93	14.64 ± 10.59	4.41 ± 3.14	<0.001
Interevent time[a,b]	398.11 ± 497.38	157.73 ± 163.52	215.18 ± 233.23	<0.001
Time maximum pick[a,b,c]	3.02 ± 4.87	7.38 ± 7.72	21.53 ± 7.52	<0.001
Maximum pick[a,c]	1.58 ± 1.52	2.34 ± 2.48	1.46 ± 1.23	<0.001
Number of relative peaks[a,c]	3.5 ± 2.66	10.71 ± 5.64	4.12 ± 2.49	<0.001
Season	53	43	30	0.260
Spring	(42.1%)34	(34.1%)16	(23.8%)10	
Summer	(56.7%)38	(26.7%)32	(16.7%)31	
Winter	(37.6%)51	(31.7%)45	(30.7%)31	
Autumn	(40.2%)	(35.4%)	(24.4%)	

P values are for comparison of clusters by Kruskal-Wallis H test with Dunn's post hoc comparisons for quantitative variables and test chi-squares for categorical variables.
Abbreviations: SD, standard deviation.
[a] $p < 0.05$ between cluster 1 and cluster 2 ($p < 0.05$).
[b] $p < 0.05$ between cluster 1 and cluster 3 ($p < 0.05$).
[c] p<:0.05 between cluster 2 and cluster 3 ($p < 0.05$).

3.4. *Hyetographs*

In cluster 1, the values for the eventś duration varies from 0.5 to 81 h. On the other hand, the amplitude of the interval is defined from 0 to 3. The rainfall intensity values in this cluster ranged from 0.5 to 11.60 mm/h. I_max value is, therefore, 11.60 mm/h. In cluster 2 the range of the variable time varies from 8.5 to 198.5 h, and the amplitude of the considered values oscillates from 0 to 9. In cluster 2, the I_max reaches 13.36 mm/h. And finally, in cluster 3 the duration varies from 1 to 48 h and the amplitude of the considered interval varies from 0 to 3. The minimum (I_min) and maximum rainfall intensity (I_max) values are 0.19 and 3.4 respectively.

The most numerous cluster No. 1 covers 42% of the analyzed precipitation events. Maximum height rises in this cluster of precipitation occur during the first third of their duration. This cluster's precipitation

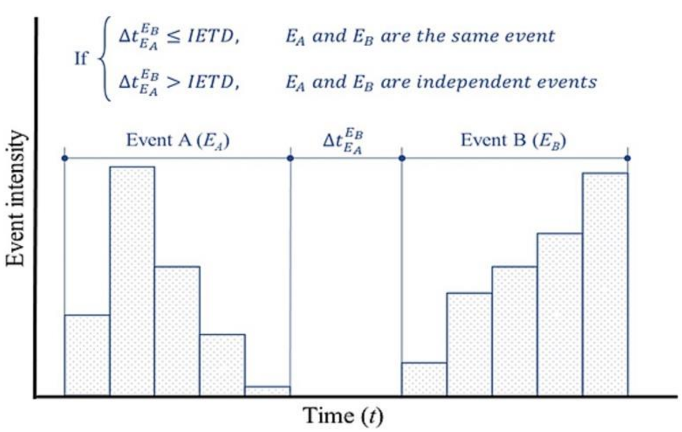

Fig. 4. Separation of independent rainfall events (IETD).

is characterized by generally even downward height fluctuations. Cluster No. 2 (33%) of events is the second most common, in which maximum height increases occur in the first half of the duration. Cluster No. 3 has a proportion of 25% and the rainfall belonging to the cluster has a similar to cluster 2. There are no obvious associations between the three clusters that were examined, which simply serves to highlight how random the events under study are. The outcomes of the hierarchical cluster analysis used to group the precipitation enabled for the verification of the maxim and relative peak. Fig. 5 shows the calculated averaged dimensionless cumulative storm rainfall hyetographs.

4. Discussion and conclusions

Despite the need for improved quantitative rainfall analysis has grown in recent years, it is not possible yet to robustly determine or predict the duration and intensity of associated extremal events such as droughts or floods and their months of onset and termination. This requires modernisation of methods dealing with recorded precipitation series processing. Necessary analytical elements of such modernization is modelled or synthetic hyetographs. The usage of data mining technologies, particularly the cluster analysis, is justified and required due to the ever-growing sets of rainfall records. The classification of storm rainfall hyetographs has already used the application of cluster analysis in the examination of the temporal distributions of rainfall. However, there are not studies using the silhouette index to make clustering algorithm, i.e. an internal clustering validation index. In addition, this study is pioneer in constructing the hyetograph considering the maximum rainfall intensity in each group found by cluster analysis and then, characterizing the clusters according to the physical characteristics of the rainfall. Therefore, this analysis becomes an easy interpretable graphical representation of the maximum intensity of the rain over time.

In conclusion, the way of identifying clusters based on the previous methodological approach has allowed to robustly differentiate the three main of hyetographs that represents the three main types of rainfall. In more detail, the results obtained in this study identify three well-differentiated clusters to obtain a multivariate characterisation of the rainfall: the first group consisted of strong intensity, moderately long-lasting events with the peak intensity centred in the first quarter, just before the event started. The second group was characterized by occurrences of long duration, moderate intensity, presumably related with a major precipitation front sustained throughout time, while the third group was characterized by events of extended duration till the maximum peak is reached with moderate intensity and duration. Hyetoclust becomes a general tool that can be applied to any meteorological/hydrological context. This new tool can assist on the prediction of events (ordinary and extremal) and the effective integration to Early Warning Systems. Through Hyetoclust application it is expected to reduce the amount of losses and damage associated to extreme hydrological phenomena.

CRediT authorship contribution statement

Carmen Patino: Conceptualization, Methodology, Formal analysis, Visualization, Investigation. **Jose-Luis Molina:** Conceptualization, Methodology, Formal analysis, Visualization, Investigation. **Fernando Espejo:** Methodology, Software, Formal analysis, Investigation. **Santiago Zazo:** Conceptualization, Methodology. **Abedin Mohammad-Hosseinpour:** Supervision, Validation, Formal analysis. **Fernando Silla:** Supervision, Validation, 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.

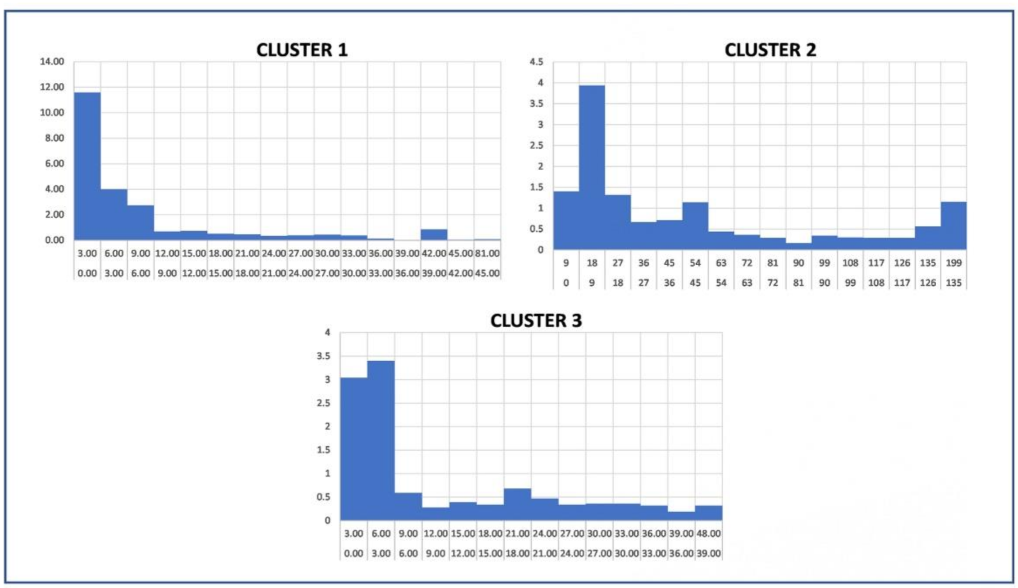

Fig. 5. Model rainfall hyetographs developed by clustering method. The horizontal axis shows the maximum rainfall intensity in cluster 1 every three hours, cluster 2 every 9 h and cluster 3 every 3 h and the vertical axis shows the vertical axis shows the time intervals.

Data availability

Data will be made available on request.

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References

Abolverdi, J., Ferdosifar, G., Khalili, D., Kamgar-Haghighi, A.A., 2016. Spatial and temporal changes of precipitation concentration in Fars province, southwestern Iran. Meteorol. Atmos. Phys. 128, 181–196. https://doi.org/10.1007/s00703-015-0414-0.

Aronica, G.T., Freni, G., 2005. Estimation of sub-hourly DDF curves using scaling properties of hourly and sub-hourly data at partially gauged site. Atmos. Res. 77, 114–123. https://doi.org/10.1016/j.atmosres.2004.10.025.

Barton, Y., Giannakaki, P., von Waldow, H., Chevalier, C., Pfahl, S., Martius, O., 2016. Clustering of Regional-Scale Extreme Precipitation Events in Southern Switzerland. Mon. Weather Rev. 144, 347–369. https://doi.org/10.1175/MWR-D-15-0205.1.

Benabdelouahab, T., Gadouali, F., Boudhar, A., Lebrini, Y., Hadria, R., Salhi, A., 2020. Analysis and trends of rainfall amounts and extreme events in the Western Mediterranean region. Theor. Appl. Climatol. 141, 309–320. https://doi.org/10.1007/s00704-020-03205-4.

Brito, T.T., Oliveira-Júnior, J.F., Lyra, G.B., Gois, G., Zeri, M., 2017. Multivariate analysis applied to monthly rainfall over Rio de Janeiro state. Brazil. Meteorol. Atmos. Phys. 129, 469–478. https://doi.org/10.1007/s00703-016-0481-x.

Chen, Y., Paschalis, A., Wang, L.P., Onof, C., 2021. Can we estimate flood frequency with point-process spatial-temporal rainfall models? J. Hydrol. 600, 126667 https://doi.org/10.1016/j.jhydrol.2021.126667.

Chen, L., Singh, V.P., 2018. Entropy-based derivation of generalized distributions for hydrometeorological frequency analysis. J. Hydrol. 557, 699–712. https://doi.org/10.1016/j.jhydrol.2017.12.066.

Chimene, C.A., Campos, J.N.B., 2020. The design flood under two approaches: synthetic storm hyetograph and observed storm hyetograph. J. Appl. Water Eng. Res. 8, 171–182. https://doi.org/10.1080/23249676.2020.1787242.

Choo, K.-S., Kang, D.-H., Kim, B.-S., 2020. Impact assessment of urban flood on traffic disruption using rainfall–depth–vehicle speed relationship. Water 12, 926. https://doi.org/10.3390/w12040926.

Costa, M.d.S., Oliveira-Júnior, J.F.d., Santos, P.J.D., Correia Filho, W.L.F., Gois, G.d., Blanco, C.J.C., Teodoro, P.E., Silva Junior, C.A.d., Santiago, D.d.B., Souza, E.d.O., Jardim, A.M.d.R.F., 2021. Rainfall extremes and drought in Northeast Brazil and its relationship with El Niño-Southern Oscillation. Int. J. Climatol. 41 (S1) https://doi.org/10.1002/joc.6835.

da Silva, F.P., Rotunno Filho, O.C., Justi da Silva, M.G.A., Sampaio, R.J., Pires, G.D., de Araújo, A.A.M., 2020. Identification of rainfall and atmospheric patterns associated with Quitandinha River flooding events in Petropolis, Rio de Janeiro (Brazil). Nat. Hazards 103, 3745–3764. https://doi.org/10.1007/s11069-020-04153-y.

Dunkerley, D., 2008. Identifying individual rain events from pluviograph records: a review with analysis of data from an Australian dryland site. Hydrol. Process. 22, 5024–5036. https://doi.org/10.1002/hyp.7122.

Dunn, O.J., 1964. Multiple comparisons using rank sums. Technometrics 6 (3), 241–252.

Fahad, S., Su, F., Khan, S.U., Naeem, M.R., Wei, K., 2023. Implementing a novel deep learning technique for rainfall forecasting via climatic variables: an approach via hierarchical clustering analysis. Sci. Total Environ. 854, 158760 https://doi.org/10.1016/j.scitotenv.2022.158760.

Freitas, E. da S., Coelho, V.H.R., Xuan, Y., Melo, D. de C.D., Gadelha, A.N., Santos, E.A., Galvão, C. de O., Ramos Filho, G.M., Barbosa, L.R., Huffman, G.J., Petersen, W.A., Almeida, C. das N., 2020. The performance of the IMERG satellite-based product in identifying sub-daily rainfall events and their properties. J. Hydrol. 589, 125128. https://doi.org/10.1016/j.jhydrol.2020.125128.

Gioia, A., Lioi, B., Totaro, V., Molfetta, M.G., Apollonio, C., Bisantino, T., Iacobellis, V., 2021. Estimation of peak discharges under different rainfall depth–duration–frequency formulations. Hydrology 8, 150. https://doi.org/10.3390/hydrology8040150.

Grace, R., Eagleson, P., 1967. A model for generating synthetic sequences of short-time-interval rainfall depths, in: Proc. Int. Hydrol. Syrup., Fort Collins, Colo.,. pp. 268–276.

Hamitouche, M., Molina, J.-L., 2022a. Event-based Bayesian causal modelling for flood hydrograph prediction, Upper Andarax intermittent stream. Spain. J. Hydrol. Reg. Stud. 44, 101260 https://doi.org/10.1016/j.ejrh.2022.101260.

Hamitouche, M., Molina, J.-L., 2022b. A review of AI methods for the prediction of high-flow extremal hydrology. Water Resour. Manag. 36, 3859–3876. https://doi.org/10.1007/s11269-022-03240-y.

Hong, M., Kim, J., Jeong, S., 2018. Rainfall intensity-duration thresholds for landslide prediction in South Korea by considering the effects of antecedent rainfall. Landslides 15, 523–534. https://doi.org/10.1007/s10346-017-0892-x.

Howard, C.D.D., 1976. Theory of storage and treatment plant overflows. J. Environ. Eng. Div. 102, 709–722. https://doi.org/10.1061/JEEGAV.0000508.

Iadanza, C., Trigila, A., Napolitano, F., 2016. Identification and characterization of rainfall events responsible for triggering of debris flows and shallow landslides. J. Hydrol. 541, 230–245. https://doi.org/10.1016/j.jhydrol.2016.01.018.

Joo, J., Lee, J., Kim, J., Jun, H., Jo, D., 2013. Inter-event time definition setting procedure for urban drainage systems. Water 6, 45–58. https://doi.org/10.3390/w6010045.

Jun, C., Qin, X., Chen, M., Seo, H., 2021. Investigating event-based temporal patterns of design rainfall in a tropical region. Hydrol. Sci. J. 66, 1986–1996. https://doi.org/10.1080/02626667.2021.1967958.

Knerr, I., Trachte, K., Garel, E., Huneau, F., Santoni, S., Bendix, J., 2020. Partitioning of large-scale and local-scale precipitation events by means of spatio-temporal precipitation regimes on corsica. Atmosphere (Basel). 11, 417. https://doi.org/10.3390/atmos11040417.

Lewis, E., Fowler, H., Alexander, L., Dunn, R., McClean, F., Barbero, R., Guerreiro, S., Li, X.-F., Blenkinsop, S., 2019. GSDR: a global sub-daily rainfall dataset. J. Clim. 32, 4715–4729. https://doi.org/10.1175/JCLI-D-18-0143.1.

Lima, A.O., Lyra, G.B., Abreu, M.C., Oliveira-Júnior, J.F., Zeri, M., Cunha-Zeri, G., 2021. Extreme rainfall events over Rio de Janeiro State, Brazil: characterization using probability distribution functions and clustering analysis. Atmos. Res. 247, 105221 https://doi.org/10.1016/j.atmosres.2020.105221.

Lyra, G.B., Oliveira-Júnior, J.F., Zeri, M., 2014. Cluster analysis applied to the spatial and temporal variability of monthly rainfall in Alagoas state, Northeast of Brazil. Int. J. Climatol. 34, 3546–3558. https://doi.org/10.1002/joc.3926.

McPhillips, L.E., Chang, H., Chester, M.V., Depietri, Y., Friedman, E., Grimm, N.B., Kominoski, J.S., McPhearson, T., Méndez-Lázaro, P., Rosi, E.J., Shafiei Shiva, J., 2018. Defining extreme events: a cross-disciplinary review. Earth's Futur. 6, 441–455. https://doi.org/10.1002/2017EF000686.

Mikołajewski, K., Ruman, M., Kosek, K., Glixelli, M., Dzimińska, P., Ziętara, P., Licznar, P., 2022. Development of cluster analysis methodology for identification of model rainfall hyetographs and its application at an urban precipitation field scale. Sci. Total Environ. 829, 154588 https://doi.org/10.1016/j.scitotenv.2022.154588.

Molina, J.-L., Espejo, F., Zazo, S., Molina, M.-C., Hamitouche, M., García-Aróstegui, J.-L., 2022. HydroPredicT_Extreme: a probabilistic method for the prediction of extremal high-flow hydrological events. J. Hydrol. 610, 127929 https://doi.org/10.1016/j.jhydrol.2022.127929.

Molina, J.-L., Zazo, S., 2018. Assessment of temporally conditioned runoff fractions in unregulated rivers. J. Hydrol. Eng. 23 https://doi.org/10.1061/(ASCE)HE.1943-5584.0001645.

Molina-Sanchis, I., Lázaro, R., Arnau-Rosalén, E., Calvo-Cases, A., 2016. Rainfall timing and runoff: the influence of the criterion for rain event separation. J. Hydrol. Hydromechanics 64, 226–236. https://doi.org/10.1515/johh-2016-0024.

Morbidelli, R., Saltalippi, C., Flammini, A., Govindaraju, R.S., 2018. Role of slope on infiltration: a review. J. Hydrol. 557, 878–886. https://doi.org/10.1016/j.jhydrol.2018.01.019.

Mrad, D., Dairi, S., Boukhari, S., Djebbar, Y., 2020. Applied multivariate analysis on annual rainfall in the northeast of Algeria. J. Water Clim. Chang. 11, 1165–1176. https://doi.org/10.2166/wcc.2019.272.

Nazeri Tahroudi, M., Ramezani, Y., Michele, C., Mirabbasi, R., 2022. Multivariate analysis of rainfall and its deficiency signatures using vine copulas. Int. J. Climatol. 42, 2005–2018. https://doi.org/10.1002/joc.7349.

O'Gorman, P.A., 2015. Precipitation extremes under climate change. Curr. Clim. Chang. Reports 1, 49–59. https://doi.org/10.1007/s40641-015-0009-3.

Restrepo-Posada, P.J., Eagleson, P.S., 1982. Identification of independent rainstorms. J. Hidrol. 55 (1-4), 303–319.

Sa'adi, Z., Shahid, S., Ismail, T., Chung, E.-S., Wang, X.-J., 2019. Trends analysis of rainfall and rainfall extremes in Sarawak, Malaysia using modified Mann-Kendall test. Meteorol. Atmos. Phys. 131 (3), 263–277.

Sahu, R., Verma, M., Ahmad, I., 2022. Segmental variability of precipitation in the Mahanadi River basin from 1901 to 2017. Geocarto Int. 1–22.

Santos, C., Brasil Neto, R., da Silva, R., Costa, S., 2019. Cluster analysis applied to spatiotemporal variability of monthly precipitation over paraíba state using tropical rainfall measuring mission (TRMM) data. Remote Sens. 11, 637. https://doi.org/10.3390/rs11060637.

Sariahmed, A., Kisiel, C., 1968. Synthesis of sequences of summer thunderstorm volumes for the Atterbury watershed in the Tucson area, in: Proc. Int. Assoc. Hydrol. Sci. Syrup. on Use of Analog and Digital Computers in Hydrology. pp. 439–447.

Thakur, N., Karmakar, S., Soni, S., 2021. Rainfall Forecasting Using Various Artificial Neural Network Techniques - A Review. Int. J. Sci. Res. Comput. Sci. Eng. Inf. Technol. 506–526. https://doi.org/10.32628/CSEIT2173159.

Tokar, A.S., 1996. Rainfall-runoff modeling in an uncertain environment. University of Maryland, College Park.

Vélez-Nicolás, M., García-López, S., Ruiz-Ortiz, V., Zazo, S., Molina, J.L., 2022. Precipitation variability and drought assessment using the SPI: application to long-term series in the strait of Gibraltar area. Water 14, 884. https://doi.org/10.3390/w14060884.

Wang, Y., Li, C., Liu, J., Yu, F., Qiu, Q., Tian, J., Zhang, M., 2017. Multivariate analysis of joint probability of different rainfall frequencies based on copulas. Water 9, 198. https://doi.org/10.3390/w9030198.

Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. J. Am. Stat. Assoc. 58 (301), 236–244.
Wartalska, K., Kaźmierczak, B., Nowakowska, M., Kotowski, A., 2020. Analysis of hyetographs for drainage system modeling. Water 12, 149. https://doi.org/10.3390/w12010149.
Wong, K.W., Wong, P.M., Gedeon, T.D., Fung, C.C., 2003. Rainfall prediction model using soft computing technique. Soft comput. - a fusion found. Methodol. Appl. 7, 434–438. https://doi.org/10.1007/s00500-002-0232-4.

Capítulo 5 “CONCLUSIONES”

5. Conclusiones

The Thesis investigates water cycle in three ways; the holistic approach in looking at rainfall patterns, partial approach through looking at morphology of rivers and in-between approach of changing stormwater management to help groundwater tables.

5-1- The conclusion of the first journal paper about partial approach with the title of “Interaction between gravel mining pits and river curvature on maximum scour depth through 2D hydraulic modelling” is as follows: Gravel mining has always been extremely important due to the rich resources of construction materials. This issue has profound impacts on rivers and their intersecting structures, one of the most important of which is the bed degradation. Moreover, it is crucial to consider that rivers are not usually straight and are generally flow a sinuous trial. In this study, an attempt has been made to investigate and understand the interaction between gravel mining pits and river curvature regarding river bed degradation.

To investigate the interacting effects of river curvature and gravel mining pits on rivers morphology, models of a channel with different curvatures, from a direct channel to a channel with high degree of curvature, were constructed using the a 2D model and the results of the simulations were analyzed.

Morphological study of river beds is a challenge due to the large amount of data produced by a 2D model and it would be extremely difficult to discover the pattern of changes. Therefore, it was decided to focus the morphological effects on a single parameter. By choosing the maximum scour depth as the most destructive morphological effect, comparison has become much understandable, i.e. while enjoy the high accuracy of the results due to the two-dimensional simulation, by focusing the results on this parameter, comparison became more mathematical and quantitative than qualitative and descriptive.

Examination of the results showed that from the direct channel to the channel with higher degree of curvature, the maximum scour depth moves from the center of the cross section toward the outer wall and maximum deposition elevation moves toward the inner wall; in addition, moving of the maximum scour depth along the channel (downstream) is visible.

As can be seen from the results, the maximum scour depth is almost always increased. However, it is clear that a curved channel without a pit will also have more degradation than a straight channel and that is due to the increase in velocity at the outer wall of the bend; therefore, the effect of the mining pit is isolated and investigated separately. For this purpose, a parameter called Δ was defined which was considered equal to the maximum scour depth with the gravel mining pit minus the maximum scour depth without it.

Changes in Δ as the net effect of mining pit in maximum scour depth could be described in three parts; a reducing wing, an extremum and an increasing wing. Increasing the curvature, the value of Δ, from direct channel to channel with light curvature of C/L=2.38 is decreased. At this point, Δ is eventually close to zero which in another word means that there are no difference in maximum scour depth between a channel with a pit and a channel without a pit at this curvature degree. Afterwards, the increasing wing of Δ-C/L diagram is formed.

Inspection of the influent parameters showed that the event is due to two simultaneous phenomena. Decreasing phenomenon which is called smoothing, is an effect of both asymmetry in channel shape and flow velocity which gradually changes “the sudden increase and decrease of depth” (the pit effect) to a smoother edge and cause the mining pit effect on maximum scour depth to decrease. With sharper curvatures, smoothing happens faster and gets softer, therefore the pit net effect on the maximum scour depth is expected to mitigate further. By increasing the curvature, the secondary flow becomes stronger and consequently intensifies the net pit effect on maximum scour depth. After a certain point (C/L=2.38), in which the effect of the both phenomena (smoothing and secondary flow) is in balance, the secondary flow effect which resonates the net pit effect on maximum scour depth will take the lead by curvature increased.

Finally, as described in the previous sections, there are several methods to understand and deal with the effects of gravel mining pit effects on rivers and their associated structures. One of the most popular and widely used methods is the macroscopic view, which usually examines the extraction of materials in the form of sediment budgets on the entire river ecosystem. These methods have their own merits and are certainly very useful in their place. However, the results of the present study clearly show that the microscopic perspective on the issue of material withdrawal from rivers is also extremely important. Clearly, as the results showed, the location of the gravel mining pits along the river can intensify the bed degradation depth or move it to a great extent. Overall, it seems that by combining these two perspectives and completing knowledge in both sectors, we could have the most appropriate understanding of this phenomenon and adopt the best strategies to manage and reduce its impacts.

5-2- The conclusion of the second journal paper about in-between approach with the title of “Improving the Sustainability of Urban Water Management through Innovative Groundwater Recharge System (GRS)” is as follows: One of the main pillars of development in human societies is the freshwater supply; without having enough renewable fresh water, no development will be sustainable. As human societies have always been developing and their population is growing rapidly, the consequent increasing water demand must be resolved. Due to the limited amount of freshwater available, groundwater is usually one of the first resources to be used as a replacement for scarcity. Excessive use of groundwater resources will lead to a drop in their level and cause many problems such as soil subsidence, reduced water quality and seawater intrusion.

Groundwater has been extracted from aquifers over the years in various locations around the world, and either the impacts have become visible in many places or will become soon; thus, providing a solution to this problem is an immediate necessity. One way to deal with these problems is to recharge groundwater artificially to compensate the lost water and bring balance to aquifers. There are many different ways in this regard, although usually these methods are not very effective in urban environments due to the need for large spaces or applicability in small basins; therefore, in this research a new approach is proposed to implement artificial recharge facilities in cities with high efficiency and without the negative aspects.

In general, the new proposed system which is called Groundwater Recharge System (GRS), works by modifying the existing stormwater management network and using it as a collector, supplier, and conveyer of water source to enter the recharge systems installed in its vicinity and through its length, while their main objective, which is to ensure safety against floods, remains intact. The design and implementation of the mentioned system in the study area showed that even in the worst-case scenario, when this system is filled only once a year, it will be able not only to resolve many of the adverse effects of groundwater overuse, but also will be able to deal with the effects of climate change impacts such as precipitation reduction and rising sea levels. Along with all these advantages, perhaps the most important features of the proposed facility are its cheap and fast construction along with the lack of need for complex technologies.

The proposed technique is also in direct line with the 6th goal of United Nations' Sustainable Development Goals (SDGs), clean water and sanitation which is described as to ensure availability and sustainable management of water and sanitation for all. The mentioned goal has 8 targets to achieve by year 2030. The groundwater recharge system has positive role in all of them, however, it is in direct line with target 6.6 (protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes) and target 6.a (expand international cooperation and capacity building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies) as the proposed technique use water harvesting to protect aquifers [54].

5-3- The conclusion of the first journal paper about holistic approach with the title of "HyetoClust method: Hyetograph design through Cluster Analysis" is as follows: Despite the need for improved quantitative rainfall analysis has grown in recent years, it is not possible yet to robustly determine or predict the duration and intensity of associated extremal events such as droughts or floods and their months of onset and termination. This requires modernisation of methods dealing with recorded precipitation series processing. Necessary analytical elements of such modernization is modelled or synthetic hyetographs. The usage of data mining technologies, particularly the cluster analysis, is justified and required due to the ever-growing sets of rainfall records. The classification of storm rainfall hyetographs has already used the application of cluster analysis in the examination of the temporal distributions of rainfall. However, there are not studies using the silhouette index to make clustering algorithm, i.e. an internal clustering validation index. In addition, this study is pioneer in constructing the hyetograph considering the maximum rainfall intensity in each group found by cluster analysis and then, characterizing the clusters according to the physical characteristics of the rainfall. Therefore, this analysis becomes an easy interpretable graphical representation of the maximum intensity of the rain over time.

In conclusion, the way of identifying clusters based on the previous methodological approach has allowed to robustly differentiate the three main of hyetographs that represents the three main types of rainfall. In more detail, the results obtained in this study identify three well-differentiated clusters to obtain a multivariate characterisation of the rainfall: the first group consisted of strong intensity, moderately long-lasting events with the peak intensity centred in the first quarter, just before the event started. The second group was characterized by occurrences of long duration, moderate intensity, presumably related with a major precipitation front sustained throughout time, while the third group was characterized by events of extended duration till the maximum peak is reached with moderate intensity and duration. Hyetoclust becomes a general tool that can be applied to any meteorological/hydrological context. This new tool can assist on the prediction of events (ordinary and extremal) and the effective integration to Early Warning Systems. Through Hyetoclust application it is expected to reduce the amount of losses and damage associated to extreme hydrological phenomena.

The Above Paragraphs In Spanish:

La Tesis investiga el ciclo del agua de tres maneras; el enfoque holístico al observar los patrones de lluvia, el enfoque parcial al observar la morfología de los ríos y el enfoque intermedio para cambiar la gestión de las aguas pluviales para ayudar a los niveles freáticos.

5-1- La conclusión del primer artículo de revista sobre el enfoque parcial con el título de “Interacción entre los pozos de minería de grava y la curvatura del río en la profundidad máxima de socavación a través del modelado hidráulico 2D” es la siguiente: La minería de grava siempre ha sido extremadamente importante debido a la ricos recursos de materiales de construcción. Este problema tiene profundos impactos en los ríos y sus estructuras que se cruzan, uno de los más importantes de los cuales es la degradación del lecho. Además, es fundamental tener en cuenta que los ríos no suelen ser rectos y generalmente discurren en un recorrido sinuoso. En este estudio, se ha intentado investigar y comprender la interacción entre las minas de grava y la curvatura del río con respecto a la degradación del lecho del río .

Para investigar los efectos interactivos de la curvatura del río y los pozos de extracción de grava en la morfología de los ríos, se construyeron modelos de un canal con diferentes curvaturas, desde un canal directo hasta un canal con un alto grado de curvatura, utilizando un modelo 2D y los resultados de las simulaciones . fueron analizados.

El estudio morfológico de los lechos de los ríos es un desafío debido a la gran cantidad de datos producidos por un modelo 2D y sería extremadamente difícil descubrir el patrón de cambios. Por tanto, se decidió centrar los efectos morfológicos en un solo parámetro. Al elegir la profundidad máxima de socavación como el efecto morfológico más destructivo, la comparación se ha vuelto mucho más comprensible, es decir , mientras se disfruta de la alta precisión de los resultados debido a la simulación bidimensional, al centrar los resultados en este parámetro, la comparación se vuelve más matemática y cuantitativa. que cualitativo y descriptivo.

El examen de los resultados mostró que desde el canal directo al canal con mayor grado de curvatura, la profundidad máxima de socavación se mueve desde el centro de la sección transversal hacia la pared exterior y la elevación máxima de deposición se mueve hacia la pared interior; Además, es visible el movimiento de la profundidad máxima de socavación a lo largo del canal (aguas abajo).

Como puede verse en los resultados, la profundidad máxima de socavación casi siempre aumenta. Sin embargo, está claro que un canal curvo sin foso también tendrá mayor degradación que un canal recto y eso se debe al aumento de velocidad en la pared exterior de la curva; por lo tanto, el efecto del tajo minero se aísla e investiga por separado. Para ello se definió un parámetro denominado Δ el cual se consideró igual a la profundidad máxima de socavación con el tajo de grava menos la profundidad máxima de socavación sin él.

Los cambios en Δ como efecto neto del tajo minero en la profundidad máxima de socavación podrían describirse en tres partes; un ala reductora, un extremo y un ala creciente. Al aumentar la curvatura, se disminuye el valor de Δ, de canal directo a canal con curvatura de luz de C/L=2,38. En este punto, Δ eventualmente se acerca a cero, lo que en otras palabras significa que no hay diferencia en la profundidad máxima de socavación entre un canal con picadura y un canal sin picadura en este grado de curvatura. Posteriormente, se forma el ala creciente del diagrama Δ-C/L.

La inspección de los parámetros del afluente mostró que el evento se debe a dos fenómenos simultáneos. El fenómeno decreciente , llamado suavizado, es un efecto de la asimetría en la forma del canal y la velocidad del flujo que cambia gradualmente "el aumento y disminución repentinos de la profundidad" (el efecto del pozo) a un borde más suave y causa el efecto del pozo minero en la profundidad máxima de socavación. disminuir. Con curvaturas más pronunciadas, el alisado ocurre más rápido y se vuelve más suave, por lo tanto, se espera que el efecto neto de la mina en la profundidad máxima de socavación se mitigue aún más. Al aumentar la curvatura, el flujo secundario se vuelve más fuerte y, en consecuencia, intensifica el efecto neto de la picadura en la profundidad máxima de socavación. Después de un cierto punto (C/L=2,38), en el que el efecto de ambos fenómenos (suavizamiento y flujo secundario) está en equilibrio, el efecto del flujo secundario que resuena el efecto neto del tajo en la profundidad máxima de socavación tomará la delantera por curvatura. aumentó.

Finalmente, como se describió en las secciones anteriores, existen varios métodos para comprender y abordar los efectos de los pozos de extracción de grava en los ríos y sus estructuras asociadas. Uno de los métodos más populares y utilizados es la vista macroscópica, que normalmente examina la extracción de materiales en forma de depósitos de sedimentos en todo el ecosistema fluvial. Estos métodos tienen sus propios méritos y ciertamente son muy útiles en su lugar. Sin embargo, los resultados del presente estudio muestran claramente que la perspectiva microscópica sobre la cuestión de la extracción de material de los ríos también es extremadamente importante. Claramente, como mostraron los resultados, la ubicación de los pozos de extracción de grava a lo largo del río puede intensificar la profundidad de degradación del lecho o desplazarlo en gran medida. En general, parece que combinando estas dos perspectivas y completando conocimientos en ambos sectores, podríamos tener la comprensión más adecuada de este fenómeno y adoptar las mejores estrategias para gestionar y reducir sus impactos.

5-2- La conclusión del segundo artículo de la revista sobre el enfoque intermedio con el título de “Mejorar la sostenibilidad de la gestión del agua urbana a través de un sistema innovador de recarga de aguas subterráneas (GRS)” es la siguiente: Uno de los principales pilares del desarrollo humano sociedades es el suministro de agua dulce; sin tener suficiente agua dulce renovable, ningún desarrollo será sostenible. Como las sociedades humanas siempre se han desarrollado y su población crece rápidamente, es necesario resolver la consiguiente creciente demanda de agua. Debido a la cantidad limitada de agua dulce disponible, el agua subterránea suele ser uno de los primeros recursos que se utiliza para reemplazar la escasez. El uso excesivo de los recursos de aguas subterráneas provocará una caída de su nivel y causará muchos problemas, como hundimiento del suelo, reducción de la calidad del agua e intrusión de agua de mar.

A lo largo de los años se ha extraído agua subterránea de acuíferos en varios lugares del mundo, y los impactos se han hecho visibles en muchos lugares o lo serán pronto; por lo tanto, proporcionar una solución a este problema es una necesidad inmediata. Una forma de abordar estos problemas es recargar artificialmente las aguas subterráneas para compensar la pérdida de agua y equilibrar los acuíferos. Existen muchas formas diferentes al respecto, aunque habitualmente estos métodos no resultan muy efectivos en entornos urbanos por la necesidad de grandes espacios o su aplicabilidad en cuencas pequeñas; por lo tanto, en esta investigación se propone un nuevo enfoque para implementar instalaciones de recarga artificial en ciudades con alta eficiencia y sin los aspectos negativos.

En general, el nuevo sistema propuesto, denominado Sistema de Recarga de Agua Subterránea (GRS), funciona modificando la red de manejo de aguas pluviales existente y utilizándola como fuente colectora, suministradora y transportadora de agua para ingresar a los sistemas de recarga instalados en sus cercanías y a través de su longitud, mientras que su principal objetivo, que es garantizar la seguridad contra las inundaciones, permanece intacto. El diseño e implementación del sistema mencionado en el área de estudio demostró que incluso en el peor de los casos, cuando este sistema se llene sólo una vez al año, podrá no sólo resolver muchos de los efectos adversos del uso excesivo del agua subterránea, sino también También podrá hacer frente a los efectos del cambio climático, como la reducción de las precipitaciones y el aumento del nivel del mar. Junto con todas estas ventajas, quizás las características más importantes de la instalación propuesta sean su construcción rápida y económica, además de la ausencia de necesidad de tecnologías complejas.

La técnica propuesta también está en línea directa con el sexto objetivo de los Objetivos de Desarrollo Sostenible (ODS) de las Naciones Unidas, agua potable y saneamiento, que se describe como garantizar la disponibilidad y la gestión sostenible del agua y el saneamiento para todos. La meta mencionada tiene 8 metas a alcanzar para el año 2030. El sistema de recarga de aguas subterráneas tiene un papel positivo en todas ellas, sin embargo, está en línea directa con la meta 6.6 (proteger y restaurar los ecosistemas relacionados con el agua, incluidas montañas, bosques, humedales, ríos, acuíferos y lagos) y la meta 6.a (ampliar la cooperación internacional y el apoyo al desarrollo de capacidades a los países en desarrollo en actividades y programas relacionados con el agua y el saneamiento , incluida la recolección de agua, la desalinización, la eficiencia hídrica, el tratamiento de aguas residuales, el reciclaje y las tecnologías de reutilización) Como técnica propuesta, se utiliza la recolección de agua para proteger los acuíferos [54].

5-3- La conclusión del primer artículo de una revista sobre enfoque holístico con el título de “ Método HyetoClust : diseño de hietograma a través del análisis de conglomerados” es la siguiente: A pesar de que la necesidad de mejorar el análisis cuantitativo de la lluvia ha aumentado en los últimos años, no es posible aún no se ha determinado o predicho de forma sólida la duración y la intensidad de los fenómenos extremos asociados, como sequías o inundaciones, y sus meses de inicio y finalización. Esto requiere la modernización de los métodos que se ocupan del procesamiento de series de precipitaciones registradas. Los elementos analíticos necesarios de dicha modernización son los hietógrafos modelados o sintéticos. El uso de tecnologías de extracción de datos, en particular el análisis de conglomerados, se justifica y es necesario debido a los conjuntos cada vez mayores de registros de precipitaciones. La clasificación de los hietógrafos de precipitaciones tormentosas ya ha utilizado la aplicación del análisis de conglomerados en el examen de las distribuciones temporales de las precipitaciones. Sin embargo, no hay estudios que utilicen el índice de silueta para crear un algoritmo de agrupamiento, es decir, un índice de validación de agrupamiento interno. Además, este estudio es pionero en construir el hietograma considerando la intensidad máxima de lluvia en cada grupo encontrada mediante análisis de conglomerados y luego, caracterizar los conglomerados según las características físicas de la lluvia. Por tanto, este análisis se convierte en una representación gráfica fácil de interpretar de la intensidad máxima de la lluvia en el tiempo.

En conclusión, la forma de identificar clusters basada en el enfoque metodológico anterior ha permitido diferenciar robustamente los tres principales hietogramas que representan los tres principales tipos de lluvia. Más detalladamente, los resultados obtenidos en este estudio identifican tres grupos bien diferenciados para obtener una caracterización multivariada de las precipitaciones: el primer grupo estuvo formado por eventos de fuerte intensidad y duración moderada, con el pico de intensidad centrado en el primer trimestre, justo antes el evento comenzó. El segundo grupo se caracterizó por eventos de larga duración, intensidad moderada, presumiblemente relacionados con un frente importante de precipitación sostenido a lo largo del tiempo, mientras que el tercer grupo se caracterizó por eventos de duración extendida hasta alcanzar el pico máximo con intensidad y duración moderada. Hyetoclust se convierte en una herramienta general que se puede aplicar a cualquier contexto meteorológico/hidrológico. Esta nueva herramienta puede ayudar en la predicción de eventos (ordinarios y extremos) y la integración efectiva a los Sistemas de Alerta Temprana. Mediante la aplicación de Hyetoclust se espera reducir la cantidad de pérdidas y daños asociados a fenómenos hidrológicos extremos.

ANEXO A

INDEXACIÓN Y FACTOR DE IMPACTO DE LAS REVISTAS

INDEXACIÓN Y FACTOR DE IMPACTO DE LAS REVISTAS

1. *"Interaction between gravel mining pits and river curvature on maximum scour depth through 2D hydraulic modelling"*

3. *"HyetoClust method: Hyetograph design through Cluster Analysis"*

Important Metrics

Journal Title:	Journal of Hydrology
Publisher:	Elsevier
ISSN:	221694
Type:	journal
Journal Scope:	Environmental Science
Country:	Netherlands
H-Index:	260
SJR:	1.67
Quartile:	Water Science and Technology (Q1)

2. *"Improving the Sustainability of Urban Water Management through Innovative Groundwater Recharge System (GRS)"*

Important Metrics

Journal Title:	Sustainability
Publisher:	MDPI AG
ISSN:	20711050
Type:	journal
Journal Scope:	Computer Science; Energy; Environmental Science; Social Sciences
Country:	Switzerland
H-Index:	136
SJR:	0.664
Quartile:	Geography, Planning and Development (Q1); Computer Networks and Communications (Q2); Energy Engineering and Power Technology (Q2); Environmental Science (miscellaneous) (Q2); Hardware and Architecture (Q2); Management, Monitoring, Policy and Law (Q2); Ren