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Geospatial Modelling Predicts Agricultural Microplastic Hotspots from Biosolid Application Risks

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Abstract: Microplastics are emerging as widespread modern pollutants, posing a variety of health and environmental risks. Microplastics are found in agriculture; they are often introduced via biosolids from wastewater treatment plants and are sold as alternatives to inorganic fertilizers. In Australia, there has been limited research on the agricultural concentrations of microplastics, and there has been no predictive modelling to identify which geographies are most at risk for pollution. Based on global emerging trends, this study uses geospatial modelling to map potential high-risk areas for agricultural microplastics within an area of the Murray-Darling Basin in New South Wales, Australia. In doing so, this study demonstrates the use of a geospatial methodology that may be used in future risk assessments, both within Australia and globally. Risk index mapping was conducted for three different pollutant transport pathways: rainfall-runoff of microplastics, in-soil retention of microplastics, and groundwater infiltration of microplastics. Particular areas of risk were identified for each transport pathway, providing visualised mapping results that represent the value of the study and its methodology.

Keywords: GIS; plastic; agriculture; sludge; risk assessment; Australia; pollutant; mapping

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1. Introduction

Globally, two megatons (Mt) of plastic were produced in 1950, and by 2015, this figure was closer to 400 Mt, with an annual compound growth rate of roughly 8% between 1950 and 2015 [1]. By the year 2050, it is estimated that 26,000 Mt of plastic waste will have been generated, and that 45% of that amount will be disposed of in landfills or the environment [1]. The majority of plastics are not fully biodegradable; however, they can break down into smaller fragmented microplastics. In general, microplastics are defined as "any solid or polymeric matrix of a regular or irregular shape, ranging from 1 mm to 5 mm in size, of primary or secondary manufacturing origin, that is water insoluble" [2].

In today's environment, microplastics are found in significant concentrations almost everywhere, e.g., in the air, atmosphere, water, the bodies of edible fish, blood, and even the snow on top of Mount Everest [3–7]. Upon exposure via contact, inhalation, or ingestion, microplastics have been shown to cause numerous negative health effects in humans and other animals, including intestinal damage and digestion disruption [8], decreased capacity for immune response systems [9], neurotoxicity (resulting in reduced learning and memory functions) [10], hormonal and endocrine system damage [11], decreased fertility, adverse effects on offspring [12], and oxidative stress in the lungs and airways (resulting in respiratory dysfunction) [13].

In agricultural contexts, microplastics have been shown to reduce soil fertility and soil microbe content [14], reduce plant growth and crop yield [15], increase soil–water evaporation [16], and decrease livestock fertility and transport to human food chains [17]. These agricultural microplastics also exhibit the potential to be transported to downstream aquatic environments [18], or infiltrate into groundwater [19], carrying adsorbed pollutants and heavy metals [20]. Microplastics are mostly introduced into agricultural settings as byproducts of wastewater treatment plant (WWTP) processes called biosolids. The use of biosolids in agriculture is based on their organic content as well as their potential to provide an environmentally friendly alternative to traditional fertilizers, promoting circular reuse as well as reducing greenhouse gas emissions associated with fertilizer production [21].

In Australia, total biosolid production is estimated to be around 349,000 tonnes of dry solids per year [22], with two-thirds of this material being applied to the soil as fertilisers or other soil-applied products [23]. Whilst there are state and federal regulations around biosolid application in Australia, current regulations neither recognise the risk of biosolids transporting microplastics to the agricultural environment nor provide any controls or measures to prevent this pollution.

Studies have shown that approximately 0.5–3% of biosolids contain microplastics [24], with concentrations of up to 287 μg/g of microplastics found in biosolid sludge [25]. According to a recent Australian study, approximately 4700 metric tons of plastics are released annually into the environment via biosolids, 3700 metric tons of which are released directly into agricultural settings [26].

In agricultural fields treated with biosolids in the long term, total microplastic concentrations have been found to be as high as 18,760 microplastics kg^{-1} in Chinese soils; 5190 microplastics kg^{-1} in Spanish soils; and 10,400 microplastics kg^{-1} in Chile [27–29]. Slightly lower concentrations were found elsewhere in Spain (~300 microplastics kg^{-1}) and in England (~900 microplastics kg^{-1}) [30,31]. There are few studies on microplastic field concentrations in Australia, but a recent study on biosolid-amended fields near Toowoomba, Queensland, found an average concentration of 1137 microplastics kg^{-1}, compared to 36 microplastics kg^{-1} at a non-amended reference site [32]. Substantial groundwater concentrations of microplastics were found in a Victorian groundwater bore, attributed to its proximity to agricultural land use, which may have been biosolid-applied land [33].

Utilising geospatial mapping techniques, this study aims to predict at-risk sites for agricultural microplastic contamination within the study area, the Murray-Darling Basin (MDB) agricultural region of New South Wales (NSW), Australia. This study focuses on three key pollutant transport pathways: the transportation of microplastics from agricultural sites via rainfall-runoff, the retention of microplastics in agricultural soils, and the transportation of microplastics into groundwater. To the best of the authors' knowledge, this applied methodology is a first in the field of microplastic research and represents a foundation for further risk assessment studies to build upon, as the literature base expands globally and within Australia.

This study employs Quantum Geographic Information Systems version 3.34.6 (QGIS), which is a widely used, free, and open-source geospatial software that enables the input, processing, analysis, and output of a wide range of map data and information [34].

2. Materials and Methods

The methodology of this study began with a scope definition and the selection of a geographical study area. Following this, the global literature base was reviewed to determine possible risk factors that promote the three key transport pathways of microplastics as an agricultural pollutant: the transportation of microplastics from agricultural sites via rainfall-runoff, the retention of microplastics in agricultural soils, and the transportation of microplastics into groundwater. Input data were then sourced to represent each of these risk factors within the study area, for each transport pathway. The study then combined the effects of these risk factors through geospatial modelling overlay techniques by standardising multivariate data sources for results-mapping production.

2.1. Study Area

The chosen study extent encompassed a portion of the Murray-Darling Basin (MDB) in the Australian state of New South Wales (NSW). NSW was chosen due to the quality and availability of spatial input data from the NSW State Government. The MDB encompasses more than 1 million square kilometres, including drainage catchments of the Murray and Darling Rivers, Australia's first and third longest rivers, respectively. The MDB produces approximately 40% of Australia's produce and is home to about 2.4 million people, including members of over 50 First Nations groups [35]. Additionally, the region is ecologically important, with 35 endangered species, 16 international wetlands, and 120 varieties of waterbirds [35]. Figure 1 illustrates the broad range of land uses within the MDB.

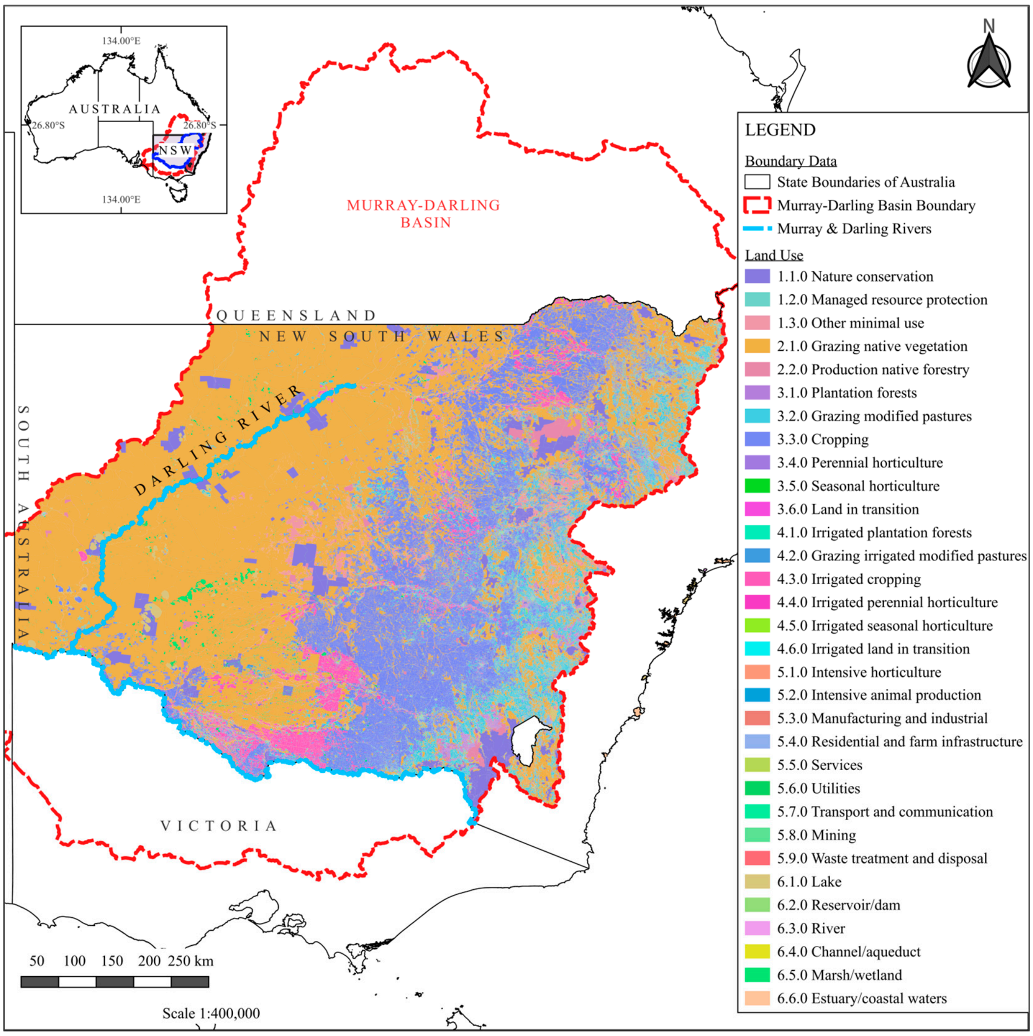

Figure 1. NSW MDB and land use. Mapping produced by using publicly available input data [36–41].

2.2. Land Use

Due to the limited categorisation of which agricultural land types are most applied with biosolids, and the lack of data toward this end in Australia, this study assumed uniform distributions of biosolid application rates across the study area and the selected agricultural land use types. Based on a review of global biosolid usage literature, two land use types were selected for the study: broadacre cropping and horticulture. Data on land use was obtained from the NSW government [40] and an overall study area polygon was drawn based on this land use. More than 90% of the chosen land use types found in the NSW MDB were captured within the study extent polygon and its boundaries were aligned to enclosed local government areas (LGAs). The study contained 50 LGAs, with boundaries and names redacted for reporting purposes. Figure 2 shows the study land use types and the study extent. Study extent polygons were divided into the three zones and aligned to internal LGA boundaries for analysis and presentation.

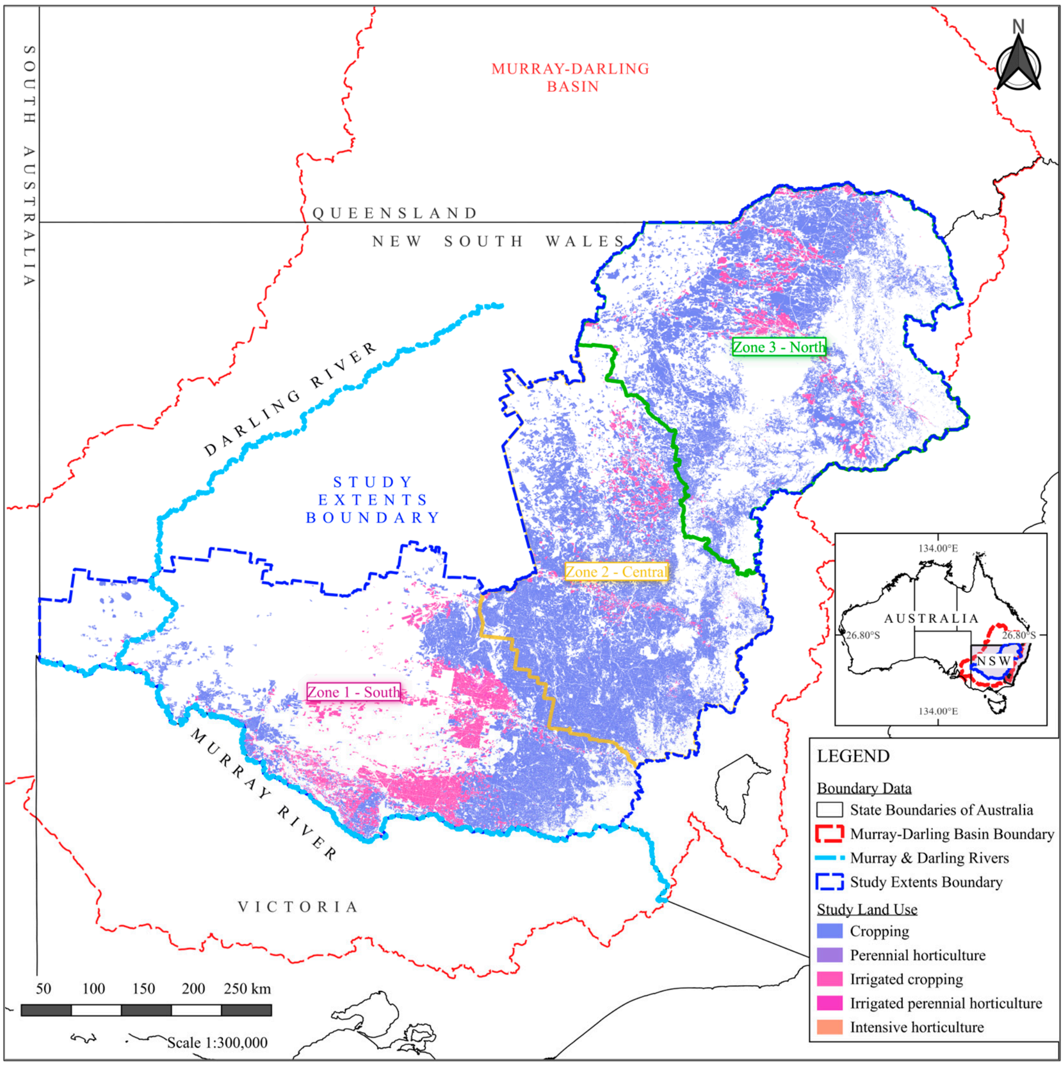

Figure 2. Study area extent and land use data. Mapping produced by using publicly available input data [37–41].

2.3. Risk Factors for Each Transport Pathway and Representative Input Data for Each Risk Factor

Potential risk factors for each of the three transport pathways were determined from the current global literature base on agricultural microplastic pollution as described below. Relevant spatial data were then sourced, or generated, for the mapping of each risk factor.

2.3.1. Rainfall-Runoff of Microplastics

In agricultural soils, microplastics are subject to rainfall-runoff cycles that ultimately transport them to downstream freshwater environments such as rivers, creeks, lakes, and further aquatic environments [18]. There are many negative effects of microplastics in aquatic environments: disrupting metabolic processes in corals [42], reducing chlorophyll absorption [43], and transporting other adsorbed pollutants such as perfluoroalkyl and polyfluoroalkyl substances (PFAS) [44]. Several key risk factors have been identified in the currently available literature, which may encourage the runoff of microplastics from applied biosolids.

Clay soils: Clay soils are the least permeable soil profiles, which reduce microplastic retention in soil during rainfall-runoff cycles. Applied biosolids are at risk of increasing runoff from poorly draining clay soils [45,46]. Figure 3 shows a modelled percentage of clay within the upper layers of soils (0–200 cm depth), within the study extent.

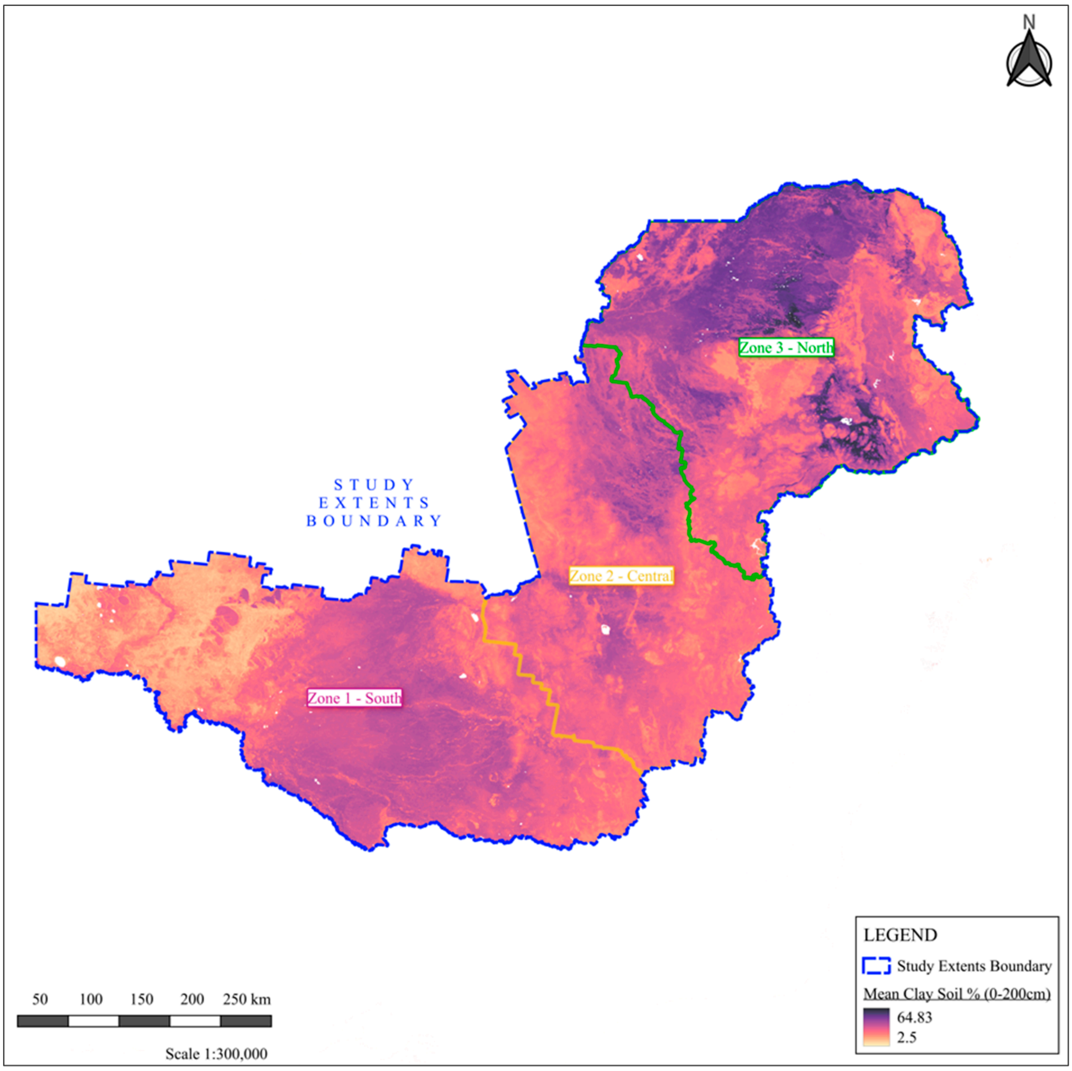

Figure 3. Mean clay soil % (0–200 cm depth). Mapping produced by using publicly available input data [46].

High average annual rainfall: In Ontario, Canada, a region that experiences a relatively high average annual rainfall of up to 1000 mm/year, one study showed that—from a large amount of biosolids applied—greater than 99% of the microplastics contained in the biosolids were unaccounted for just one year after application [47]. This could be explained by a large rainfall event shortly after the biosolid fertiliser was applied, resulting in potential mass runoff and microplastic loss [47]. Similar results were found in Hampshire, England, a study area that receives a similarly high average of 800 mm/year precipitation; researchers found that microplastic concentrations were higher during the summer when rainfall was lower, suggesting runoff may be responsible for microplastic transport [31]. In the Shaanxi province of China, researchers tested different climatic condition effects on agricultural microplastic retention with similar rates of biosolids application and land use. There was a retention of 2490 microplastics kg^{-1} in the arid northern zone versus 1700 microplastics kg^{-1} in the far southern region (which receives 1400 mm of rainfall each year) [48].

Figure 4 shows the average annual rainfall, sourced from publicly available data from the Australian Bureau of Meteorology for the period 1991–2020 [49] across the study extent.

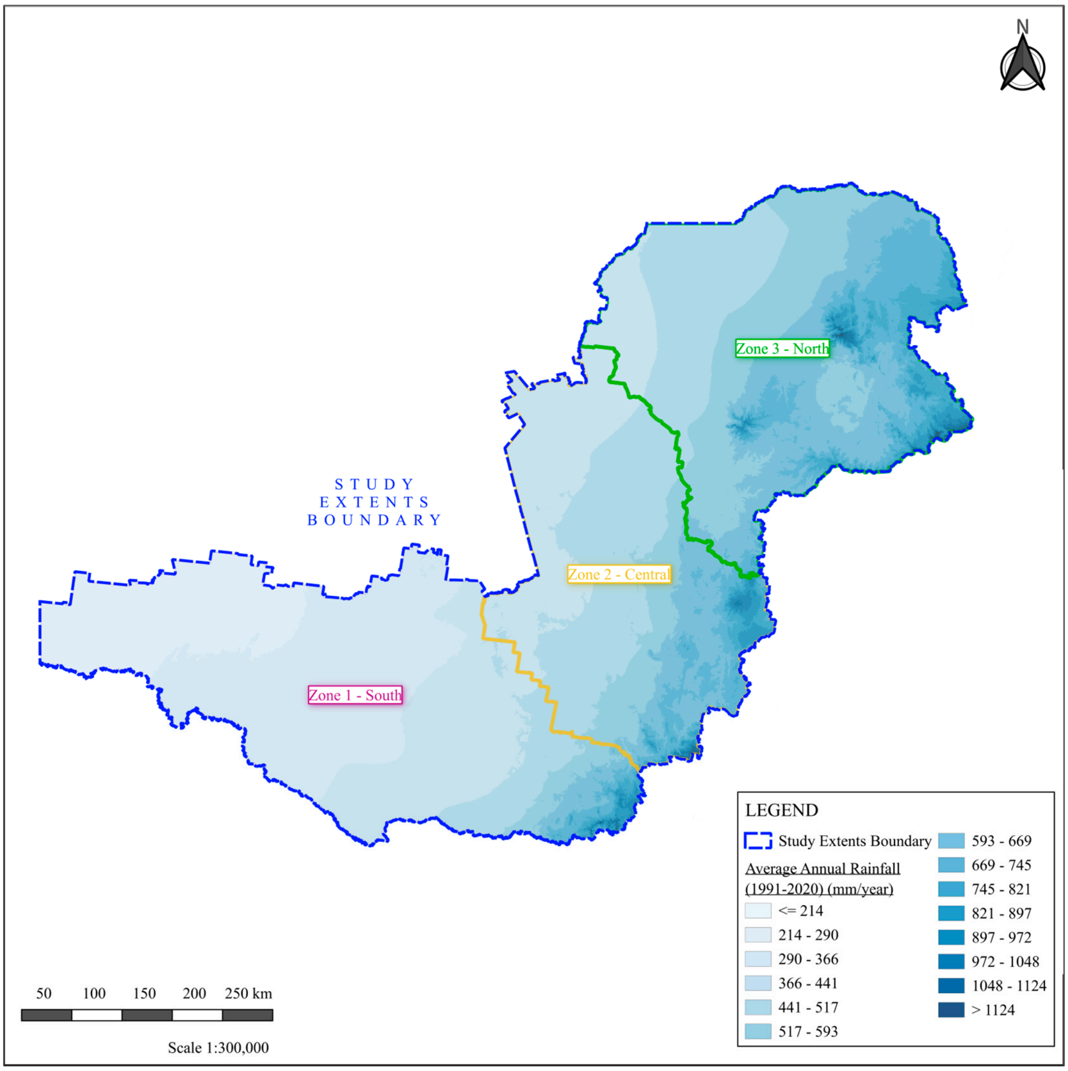

Figure 4. Average annual rainfall (1991–2020). Mapping produced by using publicly available input data [49].

Proximity to nearby waterways: The proximity of an agricultural land use parcel to a waterway plays a key role in ranking the risk of agricultural runoff entering downstream waterways. A publicly available hydrograph was obtained [38] for the entire state extent, in the form of vector line data with an attribute for the watercourse name. As shown in Figure 5a, a centroid for each study land use polygon was created and the QGIS function 'Shortest line between features' was used to find the waterway string closest to each land use polygon. Figure 5b shows the resultant lines generated by this function, with distance measurements appended as attributes to the land use parcels. Once the distance attribute was assigned to each land parcel, a rasterisation average grid was placed over the study land use extent, using the average value (distance to the nearest waterway) for each 100 × 100 m area to map this risk factor across the study extent. The results of this raster average can be seen in Figure 6.

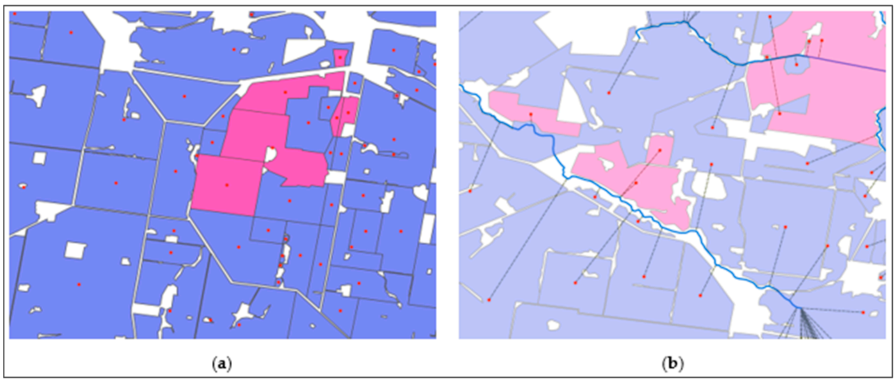
(**a**) (**b**)

Figure 5. (**a**) Study land use parcels and centroids (red dots) [40]. (**b**) Shortest distance from the study land use centroid to the nearest waterway. Mapping produced by using publicly available input data [38].

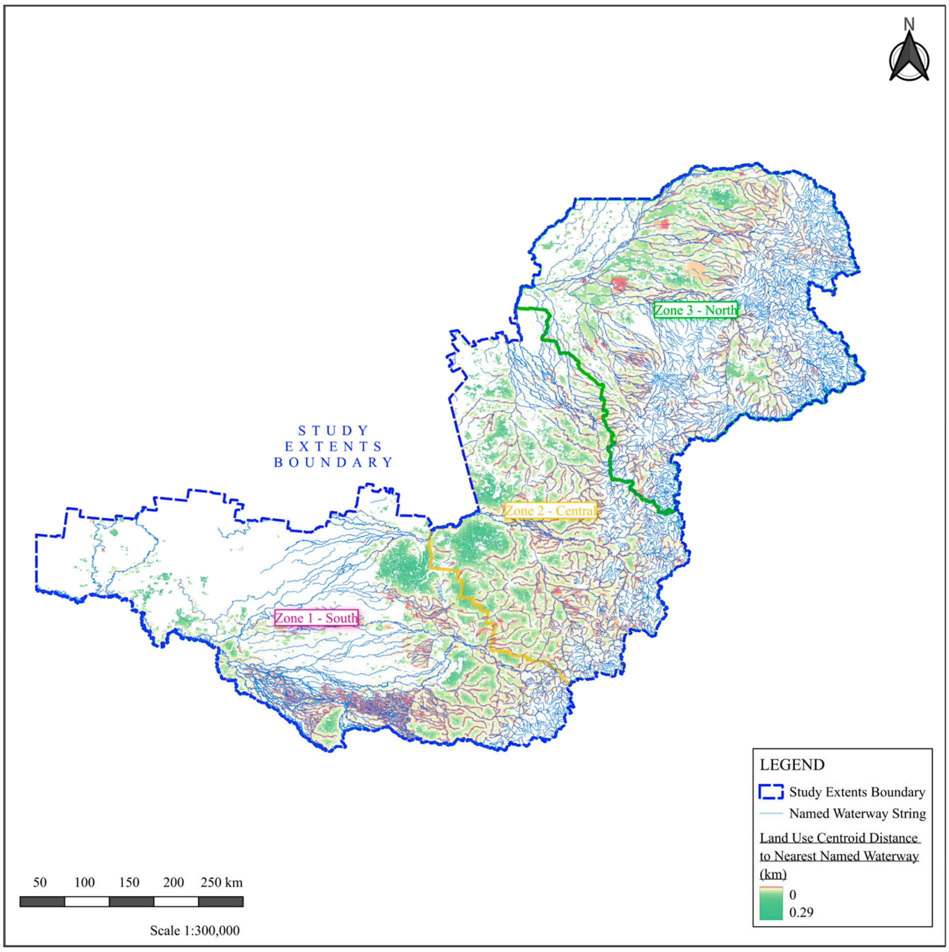

Figure 6. Land use centroid to the nearest named waterway. Mapping produced by using publicly available input data [38,40].

2.3.2. Retention of Microplastics in Soil Profiles

Agricultural soils that retain microplastics are more likely to promote reduced soil fertility and soil microbial community, leading to poor soil quality and nutrient cycling [14], reduced crop yields and plant growth [16], increased soil–water evaporation [15], and decreased livestock fertility and transport to food supply [17]. The following risk factors were identified in this study as contributing to retention:

Aridity: A study conducted in 31 agricultural fields in Melipilla, Chile, found that fields treated with 40 tonnes ha^{-1} of biosolids retained a residual concentration of 2000 microplastics kg^{-1} two years after application [29]. Similar conclusions were reached by another study in a semi-arid Spanish climate [30]. The aforementioned study in China also found that microplastic retention and concentrations were higher in the more arid northern zone, as compared to the other more temperate areas in the study [48]. Using spatial data sourced from the NSW Government [50], the 'aridity index' was used to represent aridity in the study extent. The aridity index dataset used measures the long-term balance between rainfall and net radiation [51]. The data across the study can be seen in Figure 7.

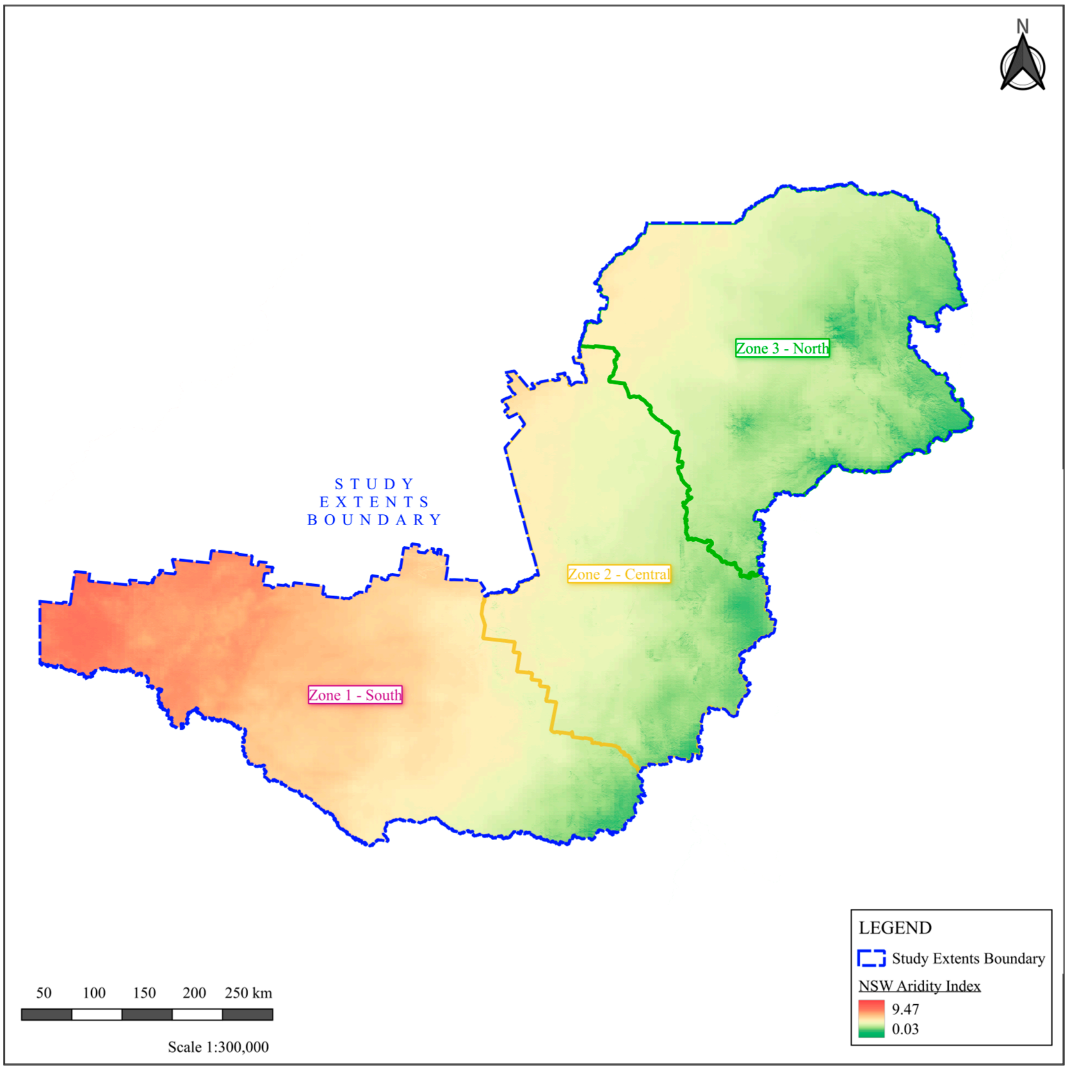

Figure 7. Aridity index. Mapping produced by using publicly available input data [50].

Horticultural land use: The use of horticultural land in agricultural soils appears to be another key variable. In the study previously mentioned [48], researchers found the highest levels of microplastic concentration in fruit-tree fields and the lowest levels in rice fields. In another study focusing on fruit orchard plantation sites amended with biosolids, a high concentration was detectable 15 years after biosolid application [52]. In France, a study covering cropping, vineyards, and fruit orchards found median concentration values of 258 microplastics kg^{-1} with maximum values ranging from 1290 microplastics kg^{-1} in crops to 3096 microplastics kg^{-1} in vineyards and fruit orchards [53].

Figure 8 shows the horticultural land use for the study extent. The study area contains over 89,000 hectares of this land use type, despite appearing sparse in the figure.

High-ionic strength soils: Several laboratory studies have shown that soil–water solutions with high-ionic strengths reduce the vertical transportation potential of microplastics, thereby increasing their retention potential in upper soil horizons [54–56]. As direct soil–water ionic strength measurements are not currently available within the study extent, salinity was used as a substitute measure, often being used to represent the ionic strength of water [57].

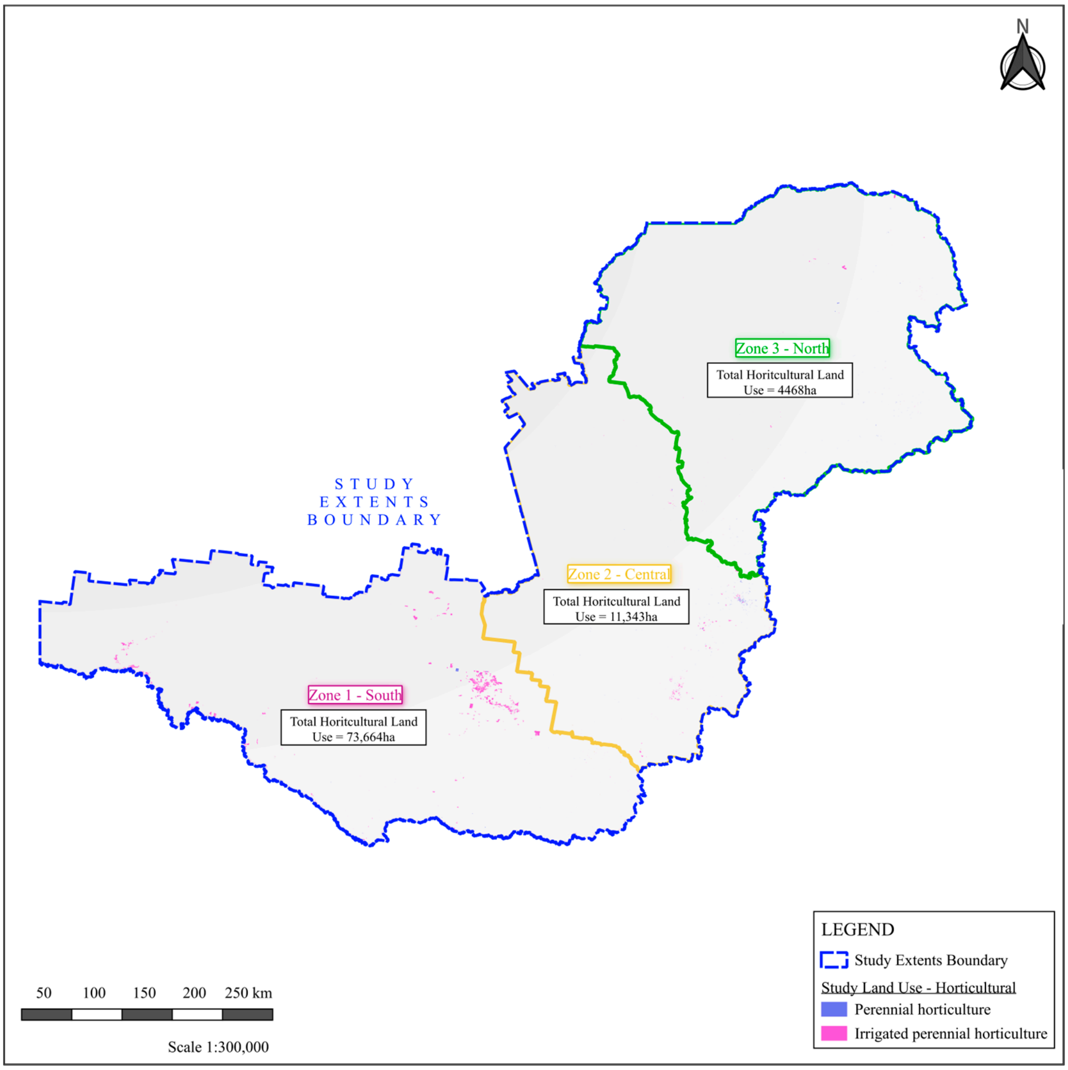

Figure 8. Horticultural land use. Mapping produced by using publicly available input data [58].

Input data were sourced from the NSW government, which provides a state-wide mapping layer for salinity hazard rankings [58]. Data were input into the project QGIS environment as vector polygons and salinity risk attributes were used to represent high- and low-salinity values. As shown in Figure 9, the original data were qualitative and replaced with numerical classes for mapping.

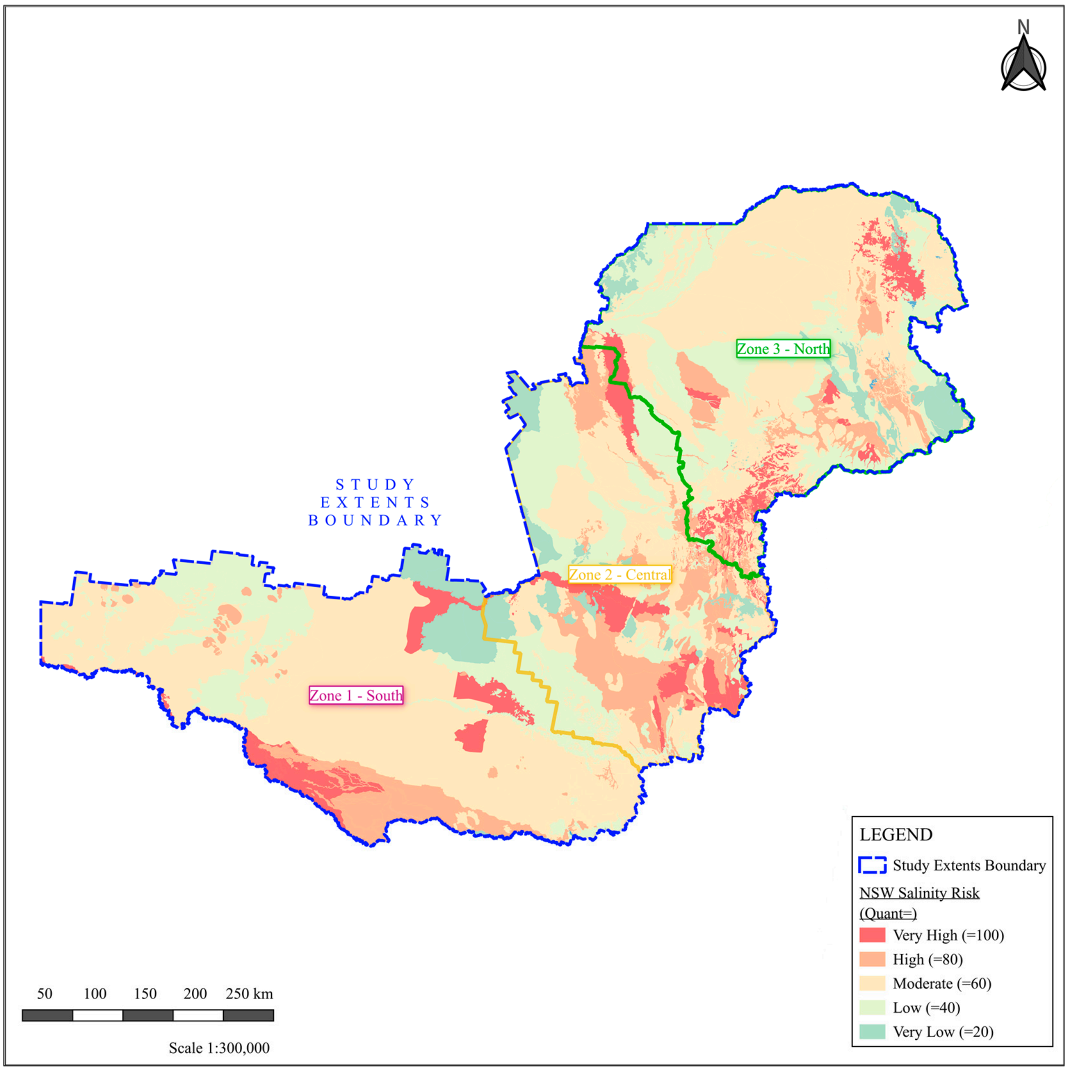

Figure 9. Salinity (used as a surrogate for ionic strength). Mapping produced by using publicly available input data [40].

2.3.3. Groundwater Infiltration of Microplastics

Whilst research is limited, recent studies have detected elevated microplastics in groundwater near agricultural activities that may have been treated with biosolids [19,59]. In a groundwater sample in the Australian state of Victoria, substantially high microplastic concentrations were found, attributed to the proximity to agricultural land that may have been fertilized with biosolid [33]. Microplastics in groundwater may reach bores used for potable water or irrigation. Eventually, they can reach more downstream waterways through groundwater aquifers. Microplastics can also adsorb pollutants such as PFAS [44] and heavy metals like cadmium [20], which can then also be transported through soils to groundwater.

Low groundwater levels: Low-lying groundwater is obviously a concern to any potential groundwater contamination. This has been acknowledged by the NSW Department of Primary Industries, in relation to biosolid amendments [45]. Groundwater mapping data were obtained as publicly available point data from the NSW government [60].

Low-ionic strength soils: As previously mentioned, high-ionic strength soil–water matrices may inhibit the vertical transportation of microplastics. In this study, it was assumed that low-ionic strength soil–water matrices might transport microplastics deeper within their profile, providing a greater risk for groundwater infiltration within low-lying areas.

High sandy soils %/hydraulic conductivity: In 2004, the NSW Department of Primary Industries identified that sandy soils were at a 'severe' risk of transporting biosolid contaminants to groundwater [45]. The risk identified is consistent with the findings of multiple studies. According to one study, microplastics transported through sandy soils of varying sizes could potentially penetrate to depths that, over time, could expose these microplastics to subterranean fauna or aquifer systems [61]. It has also been suggested that environments prone to drought cycles may increase penetration depths linearly with alternating wet/dry cycles, with the study's model predicting microplastic penetration depths of up to 7 m [61]. According to another study, copper content in sandy soils decreased with microplastic accumulation, suggesting potential copper leaching occurred as hydraulic conductivity passed water through the sandy soil [62]. In a sandy-loam soil profile containing high-density PE microplastics ranging from 48 µm to 2.0 mm, Ref. [20] found reduced soil adsorption of cadmium, as well as increased soil desorption.

Figure 10 shows the modelled percentage of sand within the upper soil layers (0–200 cm depth) from the Terrestrial Ecosystem Research Network (TERN) [46].

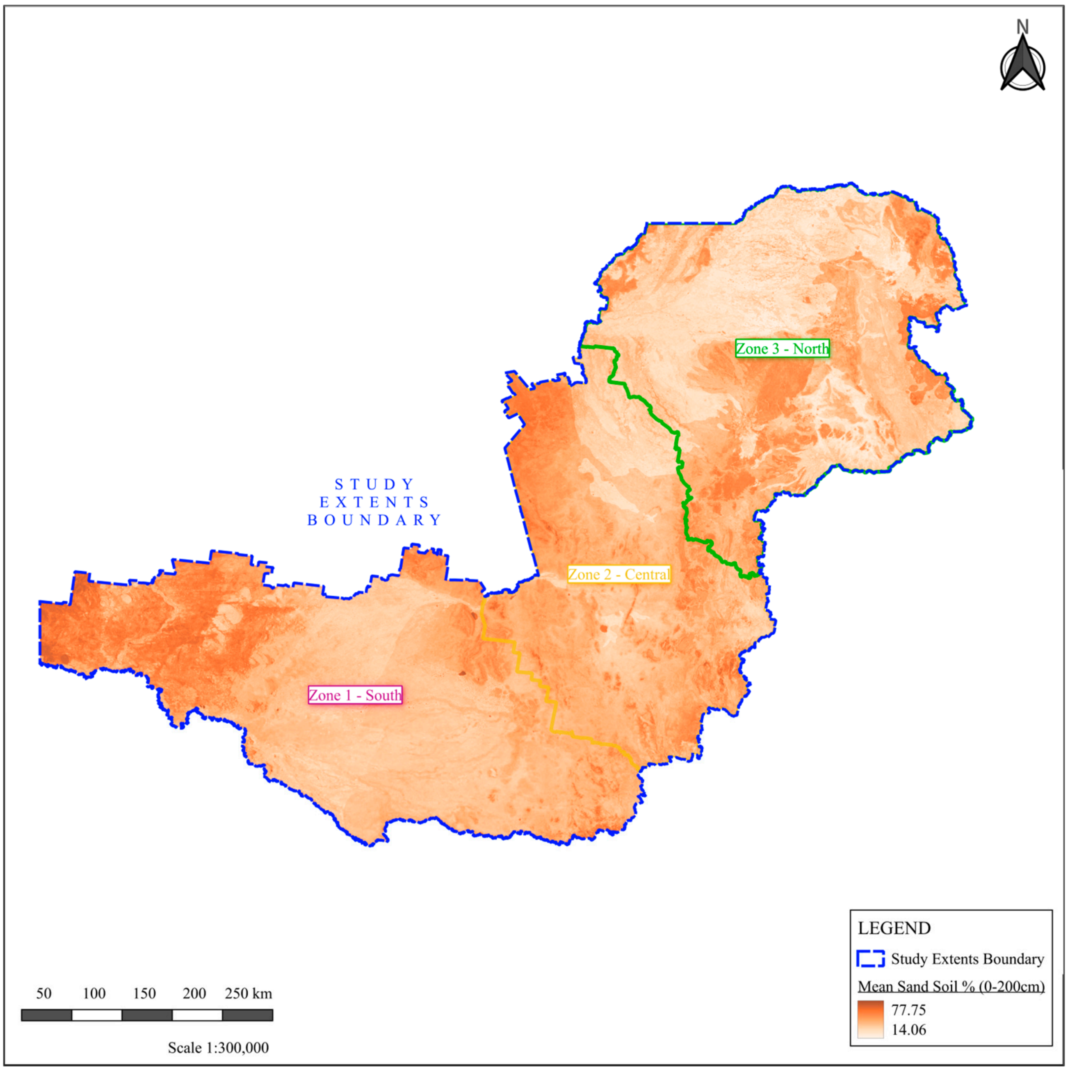

Figure 10. Mean sand soil % (0–200 cm depth). Mapping produced by using publicly available input data [46].

Table S1 in the Supplementary document provides a summary of the three study transport pathways, the risk factors that have been determined to promote these risks, and the spatial data used to represent these factors for the mapping portion of this study.

2.4. Geospatial Mapping Overlay Process for Each Transport Pathway

2.4.1. Data Reclassification into Standardised Quantiles

The different input data sources were multivariate, so QGIS was used for standardisation. First, the raster input data (raster squares of different sizes) were rescaled into 100 × 100 m squares across the study area. Then, each raster was reclassified into 100 quantile distribution classes based on the average values within these squares. Statistical quantiles were ranked according to risk factor, with higher numbers indicating greater risk (for example, the 99th percentile of annual rainfall value in the study extent was given a quantitative raster value of 99). An example of quantile reclassification, displaying the upper and lower quantiles of average annual rainfall, can be seen in Table 1 below.

Table 1. QGIS quantile reclassification example data, average annual rainfall (mm/year and corresponding quantiles 1–100).

Min (mm/Year)	Max (mm/Year)	Quantile
0.00	232.21	1
232.21	250.93	2
250.93	254.83	3
...	...	...
800.08	835.69	98
835.69	886.61	99
886.61	100,000.00	100

It should be noted that although most risk factors can be reclassified into 1–100 quantiles, a different approach was taken for the risk factors of horticultural land use and ionic strength. In the case of horticultural land use, a binary approach was used, with squares containing land use assigned a value of 100 (i.e., contributing most to the risk factors), and squares without land use assigned a value of 0. The input data for ionic strength were available as part of a qualitative set of attributes, ranking salinity risk through five categories: very low, low, moderate, high, and very high. In order to quantify ionic strength, n values (20, 40, 60, 80, 100) were assigned to the high- and low-ionic strength rasters, corresponding to the five original risk categories.

2.4.2. QGIS Raster Calculator to Combine the Effects of Risk Factors for Each Transport Pathway

The raster calculator is a tool within QGIS that enables the algebraic addition of raster squares that have the same geographical location. Figure 11 illustrates the process that occurs during raster calculator addition. To produce a raster map output that is representative of the risk index across the study extent, raster addition was applied to each transport pathway to sum the reclassified risk factor rasters. Each risk factor for each transport pathway was added to the other risk factors in that pathway. As shown in Figure 12, the study risk factors were reclassified into quantile distributions, and the raster calculations were added for each transport pathway. Based on the ascending ranking of all processed quantile risk factor data, a higher sum resulting from the addition process indicates a raster square (100 × 100-meter geographical area) at a higher risk. For each transport pathway, multiple risk factors were identified. This resultant number was normalised by dividing the sum of the raster addition by the number of risk factors for that transport pathway, resulting in an integer between 1 and 100 for any given results raster.

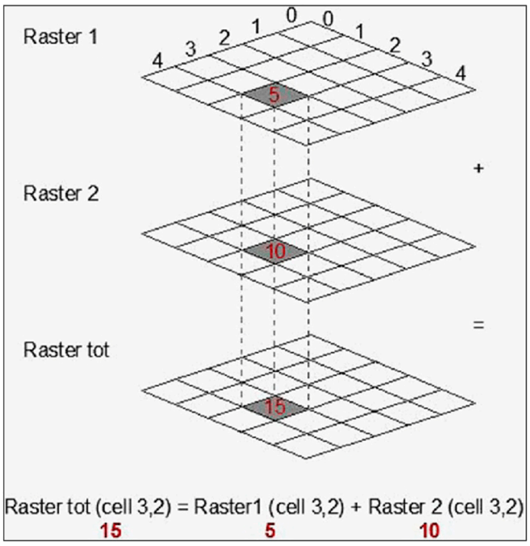

Figure 11. Raster calculator addition process. Image reproduced from [63], under CC BY 4.0 license.

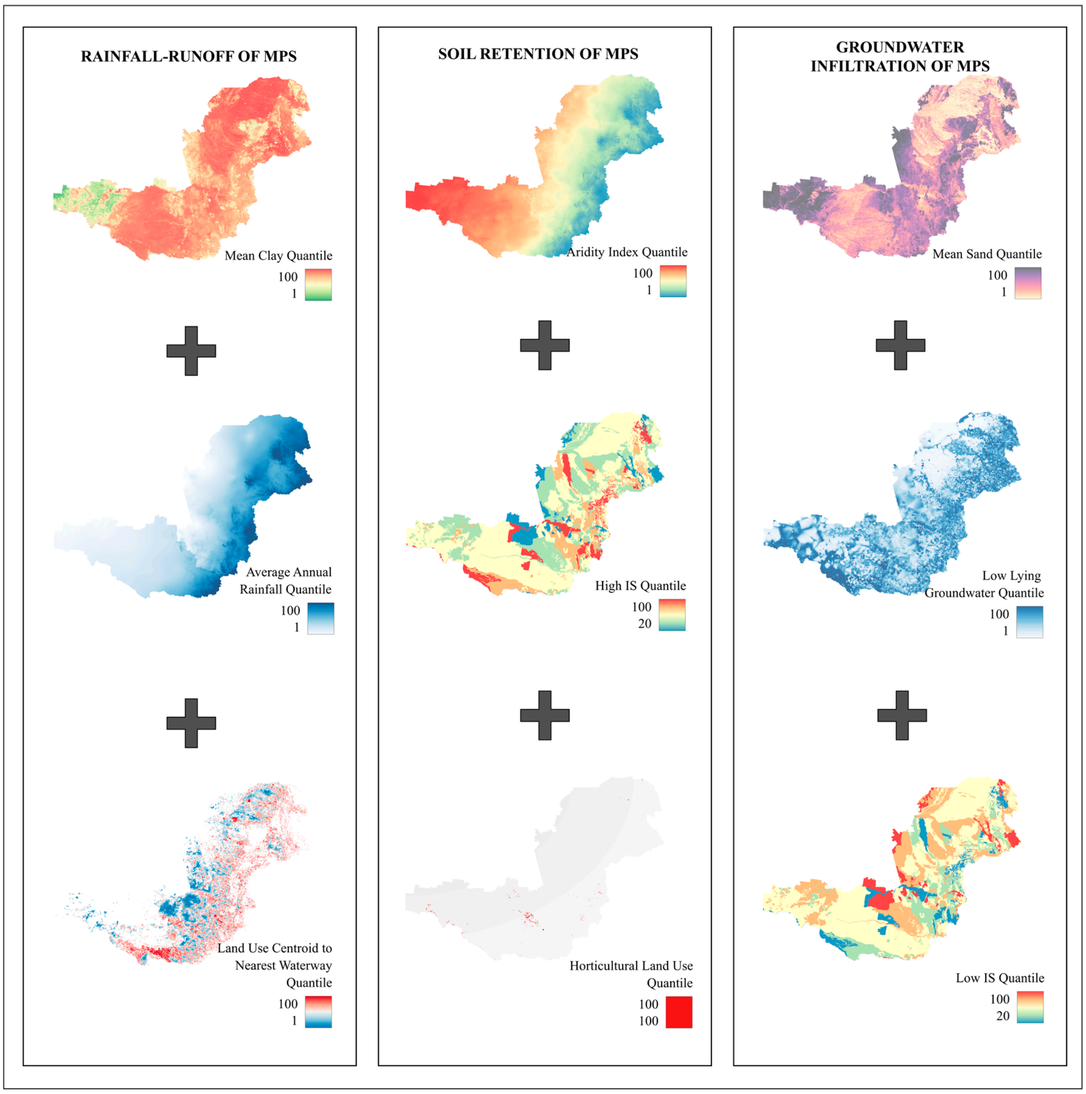

Figure 12. Quantile reclassification and raster addition of risk factors for each transport pathway.

Results rasters were 'clipped' to the extent of the study land use within the study areas. Zonal statistics were generated at both a high level for comparison of the three zones and at a more granular level by way of local government areas within the study area.

QGIS zonal statistics were also used to average the results rasters for each contained LGA polygon. The results for each of the transport pathways were ranked alongside the contributing study land use area within each LGA. The weighted mean ranking was developed by taking into consideration the risk associated with each transport pathway, as well as the contributing land use area of each LGA.

3. Results

3.1. Rainfall-Runoff of Microplastics

The risk index mapped for rainfall-runoff from microplastics across the study extent is shown in Figure 13. A general trend is observed toward the eastern areas of the study being at a higher risk for this transport pathway. The central zone displays the highest level of general risk, as indicated by its mean risk index value of 30.49. A low-risk profile is displayed in the southern zone with a mean value of 15.80; however, there is an isolated high-risk pocket adjacent to the eastern extent of the Murray River within the southern zone. The northern zone, with a mean risk index value of 24.13, displays less concentrated areas of risk than the southern zone.

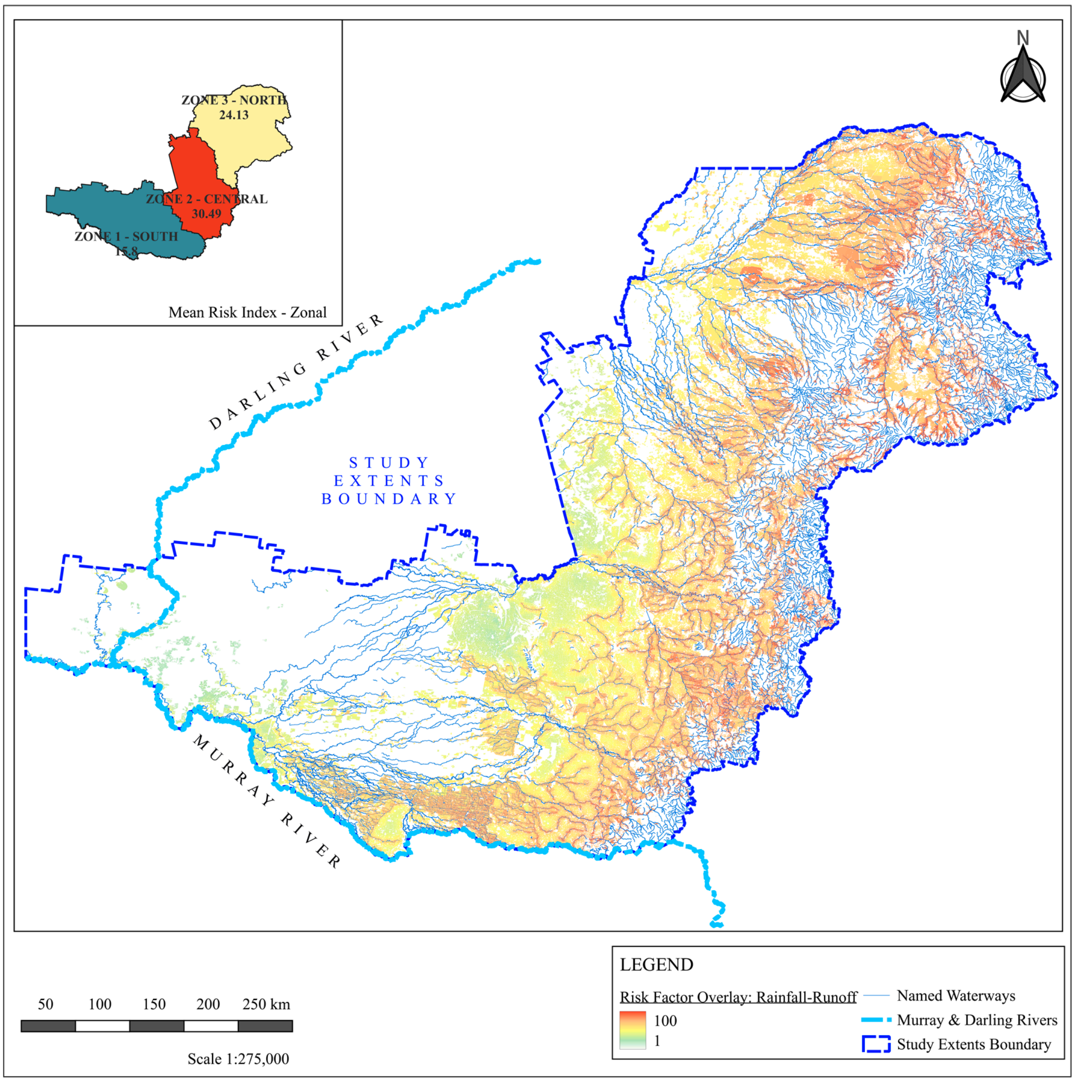

Figure 13. Results—rainfall-runoff of microplastics.

3.2. Retention of Microplastics in Soil Profiles

Based on the results raster presented in Figure 14, areas with the greatest risk of retaining microplastics in their soils can be identified. In general, there is a greater risk along the south boundary of the study area, adjacent to the Murray River, as well as smaller pockets of very high-risk zones where horticultural land use is present. The southern zone is at the highest risk, with a risk index value of 45.04. Both the central and northern zones are at similar levels of risk, with mean values of 33.64 and 29.61.

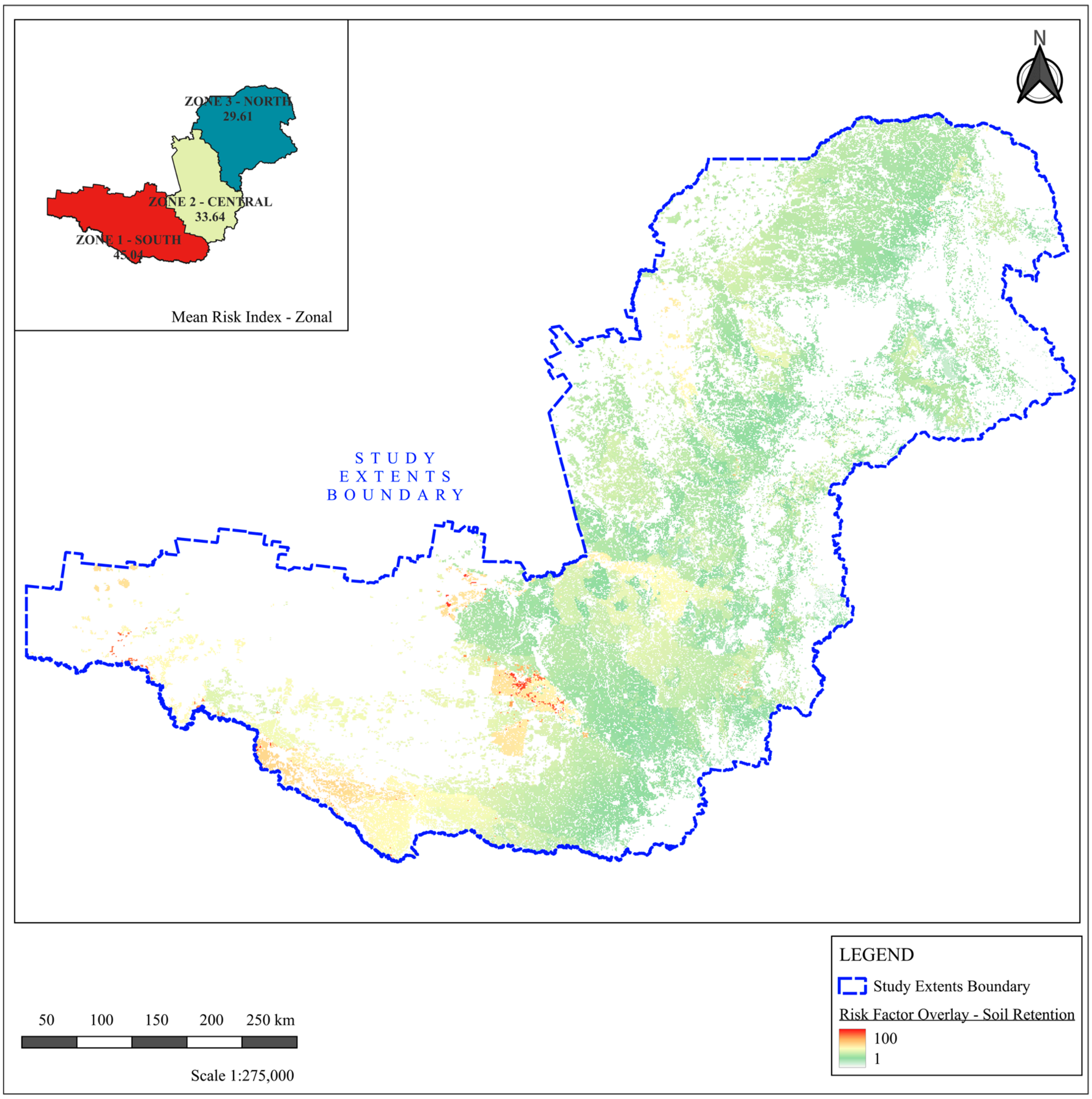

Figure 14. Results—soil retention of microplastics.

3.3. Groundwater Infiltration of Microplastics

The results of the risk mapping for groundwater infiltration of microplastics are shown in Figure 15. Based on the results, high risk is generally observed in the central-west and central-east zones of the study area, with smaller pockets found in the south-western zone. Overall, the southern zone has the highest mean risk value of 56.26, closely followed by the central zone, which has a mean value of 55.00. In addition to the zonal statistics outlined above for each transport pathway, a generalised statistical analysis was performed for each of the three transport pathways over the entire study area. Table 2 provides a statistical overview of this analysis.

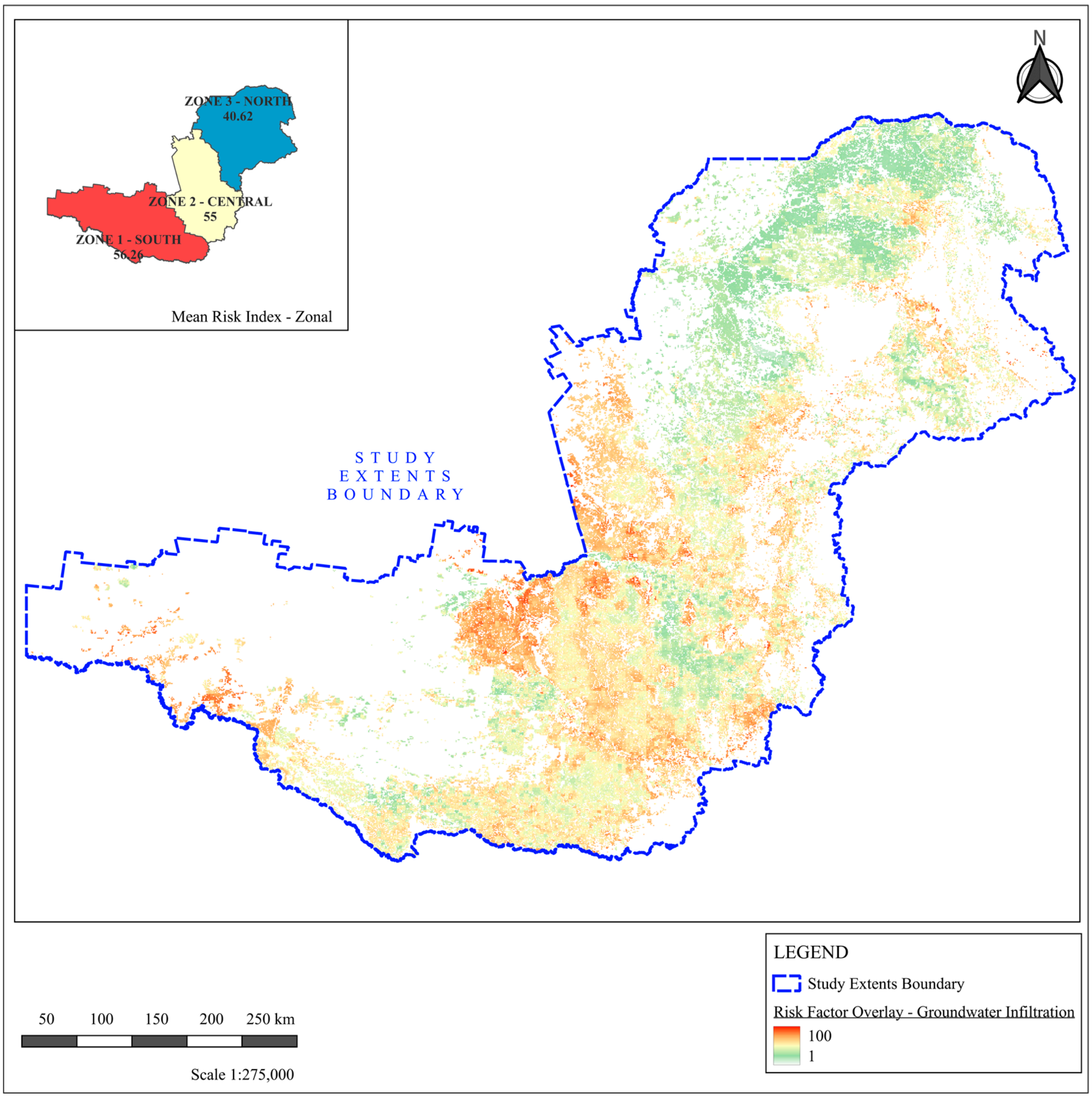

Figure 15. Results—groundwater infiltration of microplastics.

Table 2. Risk factor overlay results raster zonal statistics.

Transport Pathway	Min Value	Max Value	Range	Mean Value	Standard Deviation
Rainfall-runoff of microplastics	0.431	97.667	97.236	9.661	23.687
Soil retention of microplastics	7.333	99.333	92.000	35.581	9.588
Groundwater infiltration of microplastics	10.120	98.713	88.593	50.683	15.038

3.4. Local Government Area Results

The list of local government areas (LGAs) that are most at risk within the study extent can be found in Table 3. In the results presentation, the names of LGAs are redacted.

Table 3. Risk factor overlay results by LGA/ranking. Colour graduation from green (low risk) to red (high risk) are used in the rankings.

LGA	Study Zone	Study Land Use Area (1)	Rainfall-Runoff Risk (2)	Soil Retention Risk (3)	Ground Water Risk (4)	Mean Rank (1,2,3,4)
A	1-South	6	22.5	2	4	8.625
B	3-North	1	11	22	11.5	11.375
C	3-North	3	18.5	15	9	11.375
D	1-South	5	25	10	7.5	11.875
E	2-Central	4	22	14	9	12.25
F	2-Central	2	22.5	18	10	13.125
G	3-North	8	17.5	17	12.5	13.75
H	1-South	9	22.5	13	11	13.875
I	2-Central	15	20	12	13.5	15.125
J	1-South	17	26	8	12.5	15.875
K	2-Central	16	23	11	13.5	15.875
L	2-Central	11	11.5	24	17.5	16
M	2-Central	10	27	16	13	16.5
N	3-North	7	10.5	33	20	17.625
O	2-Central	12	19	23	17.5	17.875
P	1-South	13	27	19	16	18.75
Q	2-Central	14	21.5	25	19.5	20
R	1-South	29	28.5	7	18	20.625
S	3-North	18	14	28	23	20.75
T	1-South	21	26	21	21	22.25
U	1-South	33	27.5	9	21	22.625
V	2-Central	23	27.5	20	21.5	23
W	1-South	36	37	1	18.5	23.125
X	3-North	20	18.5	31	25.5	23.75
Y	3-North	22	15	32	27	24
Z	1-South	35	40.5	5	20	25.125
AA	2-Central	26	23	26	26	25.25
AB	3-North	27	21	27	27	25.5
AC	1-South	41	39	3	22	26.25
AD	1-South	19	21	37	28	26.25
AE	1-South	39	43	4	21.5	26.875
AF	2-Central	25	29	30	27.5	27.875
AG	3-North	24	21.5	36	30	27.875
AH	1-South	42	42	6	24	28.5
AI	2-Central	31	27.5	29	30	29.375
AJ	2-Central	32	22.5	35	33.5	30.75
AK	1-South	28	23	40	34	31.25
AL	3-North	30	19.5	41	35.5	31.5
AM	2-Central	34	22.5	38	36	32.625
AN	2-Central	37	26.5	34	35.5	33.25
AO	3-North	38	20	39	38.5	33.875
AP	3-North	40	22	43	41.5	36.625
AQ	2-Central	43	24.5	44	43.5	38.75
AR	1-South	46	26.5	42	44	39.625
AS	2-Central	44	24.5	46	45	39.875
AT	3-North	47	24	45	46	40.5
AU	3-North	45	24	47	46	40.5

4. Discussion

This GIS-based geospatial modelling study examined three key pathways for the transport of agricultural microplastics as generated by biosolid applications in the study area in the Australian state of New South Wales (NSW). Whilst the study focused on this discrete Australian area, we believe that the applicability of the methodology represents a foundation for similar studies across various global scales. This approach could contribute to the understanding of microplastic pollution risks from biosolid application.

Since there are limited research studies on the risk assessments of particular locations, actual field concentrations, and transport behaviours of agricultural microplastics in Australia, this study developed a set of risk factors that contribute to the three transport pathways by using emerging trends from the global literature base. Using publicly available high-quality spatial input data, these risk factors were mapped and subsequently overlaid to determine the risks associated with each method of transport.

According to study results, regarding the rainfall-runoff of microplastics, a greater risk was observed in the eastern regions of the NSW Murray-Darling Basin (MDB), where average annual rainfall is high, and aridity is low. Additionally, a localised region of high risk was observed in the southern portion of the study area, adjacent to the Murray River, where agricultural properties are in relatively close proximity to waterways (mostly irrigation channels draining to natural streams, creeks, and rivers).

The southern extent of the New South Wales Murray-Darling Basin is more likely to retain microplastics in soil profiles, with high-risk areas generally found in small pockets of horticultural land use, indicating the importance of this risk factor. From the mapping, medium- to high-risk areas of agricultural land adjacent to the Murray River appeared once again, in a region that is relatively arid and contains soils of high potential ionic strength.

According to the risk mapping for groundwater infiltration of microplastics, the western and southern zones of the study area were generally at the highest relative risk, with large areas at medium to high risk. High-risk areas were again found near the Murray River in concentrations of agricultural land, representing an emerging trend from all three transport pathway risk assessments.

While the study results may be limited by its broad area and assumptions made in lieu of present data in an emerging area of research, the methodology used in this study represents a novel foundational framework for the development of similar future risk assessments. By incorporating future research into the field concentrations and transport behaviours of agricultural microplastics, such risk assessments can present more high-resolution mapping, highlighting to policymakers and the agricultural industry areas of the agricultural landscape that are appropriate for biosolid amendment, and those that should be avoided to prevent the risk of microplastic pollution and downstream effects.

5. Conclusions

Globally, plastic production and consumption are on the rise and microplastic particles (microplastics), broken-down forms of these plastics, are emerging as major pollutants. The use of biosolids, which are wastewater treatment plant byproducts sold to the agriculture industry as green alternatives to inorganic fertilizers, is causing microplastics to reach agricultural settings in huge quantities. It has been shown that microplastics may cause significant environmental and ecological harm in agricultural settings, with certain risk factors increasing the likelihood that microplastics will accumulate in soils, run off into nearby waterways, or penetrate groundwater once they are introduced to agricultural settings.

This study used a GIS-based methodology to analyse a portion of the Murray-Darling Basin in New South Wales, Australia, overlaying risk factors associated with three key pathways of microplastic pollution: rainfall-runoff, soil retention, and groundwater infiltration. Through the standardisation of multivariate input data, this study was able to identify particular areas of risk for each transport pathway and map them clearly. Identifying these areas of greatest risk will allow targeted future field investigations within Australia, and the novelty of the methodology applied will provide a foundation for global studies to undertake similar investigative mapping.

This study was limited by the lack of research in the field of agricultural microplastic pollution, and future studies should verify the accuracy of mapping through field investigations and empirical studies.

A similar GIS methodology to that used in this study is applicable globally, at various scales of study, with a multitude of possibilities for input data and risk factor overlay, as the literature base develops.

Within Australia, it is recommended that further investigations be conducted to determine the actual areas that are applied with biosolids, the levels of microplastic concentrations in different types of agricultural land use, and the concentrations of microplastics in downstream waterways and groundwater near agricultural land use.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy15010047/s1, Table S1: Risk factors, categories, sources, and spatial data and sources used.

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References

1. Geyer, R.; Jambeck, J.R.; Law, K.L. Production, Use, and Fate of All Plastics Ever Made. *Sci. Adv.* **2017**, *3*, e1700782. [CrossRef]
2. Frias, J.P.G.L.; Nash, R. Microplastics: Finding a Consensus on the Definition. *Mar. Pollut. Bull.* **2019**, *138*, 145–147. [CrossRef] [PubMed]
3. O'Brien, S.; Rauert, C.; Ribeiro, F.; Okoffo, E.D.; Burrows, S.D.; O'Brien, J.W.; Wang, X.; Wright, S.L.; Thomas, K.V. There's Something in the Air: A Review of Sources, Prevalence and Behaviour of microplastics in the Atmosphere. *Sci. Total Environ.* **2023**, *874*, 162193. [CrossRef] [PubMed]
4. Gambino, I.; Bagordo, F.; Grassi, T.; Panico, A.; De Donno, A. Occurrence of microplastics in Tap and Bottled Water: Current Knowledge. *Int. J. Environ.* **2022**, *19*, 5283. [CrossRef]
5. Abbasi, S.; Soltani, N.; Keshavarzi, B.; Moore, F.; Turner, A.; Hassanaghaei, M. Microplastics in Different Tissues of Fish and Prawn from the Musa Estuary, Persian Gulf. *Chemosphere* **2018**, *205*, 80–87. [CrossRef] [PubMed]
6. Leslie, H.A.; van Velzen, M.J.M.; Brandsma, S.H.; Vethaak, A.D.; Garcia-Vallejo, J.J.; Lamoree, M.H. Discovery and Quantification of Plastic Particle Pollution in Human Blood. *Environ. Int.* **2022**, *163*, 107199. [CrossRef]
7. Napper, I.E.; Davies, B.F.R.; Clifford, H.; Elvin, S.; Koldewey, H.J.; Mayewski, P.A.; Miner, K.R.; Potocki, M.; Elmore, A.C.; Gajurel, A.P.; et al. Reaching New Heights in Plastic Pollution—Preliminary Findings of microplastics on Mount Everest. *One Earth* **2020**, *3*, 621–630. [CrossRef]
8. Kang, H.-M.; Byeon, E.; Jeong, H.; Kim, M.-S.; Chen, Q.; Lee, J.-S. Different Effects of Nano- and microplastics on Oxidative Status and Gut Microbiota in the Marine Medaka *Oryzias Melastigma*. *J. Hazard. Mater.* **2021**, *405*, 124207. [CrossRef]
9. Liu, S.; Li, H.; Wang, J.; Wu, B.; Guo, X. Polystyrene microplastics Aggravate Inflammatory Damage in Mice with Intestinal Immune Imbalance. *Sci. Total Environ.* **2022**, *833*, 155198. [CrossRef]
10. Jin, H.; Yang, C.; Jiang, C.; Li, L.; Pan, M.; Li, D.; Han, X.; Ding, J. Evaluation of Neurotoxicity in BALB/c Mice Following Chronic Exposure to Polystyrene microplastics. *Environ. Health Perspect.* **2022**, *130*, 107002. [CrossRef]
11. Vandenberg, L.N.; Luthi, D.; Quinerly, D. Plastic Bodies in a Plastic World: Multi-Disciplinary Approaches to Study Endocrine Disrupting Chemicals. *J. Clean. Prod.* **2017**, *140*, 373–385. [CrossRef]

12. Park, E.-J.; Han, J.-S.; Park, E.-J.; Seong, E.; Lee, G.-H.; Kim, D.-W.; Son, H.-Y.; Han, H.-Y.; Lee, B.-S. Repeated-Oral Dose Toxicity of Polyethylene microplastics and the Possible Implications on Reproduction and Development of the next Generation. *Toxicol. Lett.* **2020**, *324*, 75–85. [CrossRef] [PubMed]
13. Wright, S.L.; Kelly, F.J. Plastic and Human Health: A Micro Issue? *Env. Sci. Technol.* **2017**, *51*, 6634–6647. [CrossRef] [PubMed]
14. Qian, H.; Zhang, M.; Liu, G.; Lu, T.; Qu, Q.; Du, B.; Pan, X. Effects of Soil Residual Plastic Film on Soil Microbial Community Structure and Fertility. *Water Air Soil Pollut.* **2018**, *229*, 261. [CrossRef]
15. Wan, Y.; Wu, C.; Xue, Q.; Hui, X. Effects of Plastic Contamination on Water Evaporation and Desiccation Cracking in Soil. *Sci. Total Environ.* **2019**, *654*, 576–582. [CrossRef]
16. Wu, X.; Liu, Y.; Yin, S.; Xiao, K.; Xiong, Q.; Bian, S.; Liang, S.; Hou, H.; Hu, J.; Yang, J. Metabolomics Revealing the Response of Rice (*Oryza Sativa*, L.) Exposed to Polystyrene microplastics. *Environ. Pollut.* **2020**, *266*, 115159. [CrossRef]
17. Urli, S.; Pause, F.C.; Crociati, M.; Baufeld, A.; Monaci, M.; Stradaioli, G. Impact of microplastics and Nanoplastics on Livestock Health: An Emerging Risk for Reproductive Efficiency. *Animals* **2023**, *13*, 1132. [CrossRef]
18. Wang, J.; Bucci, K.; Helm, P.A.; Hoellein, T.; Hoffman, M.J.; Rooney, R.; Rochman, C.M. Runoff and Discharge Pathways of microplastics into Freshwater Ecosystems: A Systematic Review and Meta-Analysis. *FACETS* **2022**, *7*, 1473–1492. [CrossRef]
19. Abel, J. Fluctuations of Microplastic Concentrations in Groundwater and a Rural Creek Relating to Seasonal Farming Practices. In Proceedings of the 2024 Emerging Contaminants in the Environment Conference (ECEC24), Virtual, 24–25 April 2024.
20. Zhang, S.; Han, B.; Sun, Y.; Wang, F. Microplastics Influence the Adsorption and Desorption Characteristics of Cd in an Agricultural Soil. *J. Hazard. Mater.* **2020**, *388*, 121775. [CrossRef]
21. Marchuk, S.; Tait, S.; Sinha, P.; Harris, P.; Antille, D.L.; McCabe, B.K. Biosolids-Derived Fertilisers: A Review of Challenges and Opportunities. *Sci. Total Environ.* **2023**, *875*, 162555. [CrossRef]
22. ANZBP. Australian Biosolids Statistics. Available online: https://www.biosolids.com.au/guidelines/australian-biosolids-statistics/ (accessed on 9 March 2024).
23. Ziajahromi, S.; Slynkova, N.; Dwyer, J.; Griffith, M.; Fernandes, M.; Jaeger, J.E.; Leusch, F.D.L. Comprehensive Assessment of microplastics in Australian Biosolids: Abundance, Seasonal Variation and Potential Transport to Agroecosystems. *Water Res.* **2024**, *250*, 121071. [CrossRef] [PubMed]
24. Mohajerani, A.; Karabatak, B. Microplastics and Pollutants in Biosolids Have Contaminated Agricultural Soils: An Analytical Study and a Proposal to Cease the Use of Biosolids in Farmlands and Utilise Them in Sustainable Bricks. *Waste Manag.* **2020**, *107*, 252–265. [CrossRef]
25. Harley-Nyang, D.; Memon, F.A.; Jones, N.; Galloway, T. Investigation and Analysis of microplastics in Sewage Sludge and Biosolids: A Case Study from One Wastewater Treatment Works in the UK. *Sci. Total Environ.* **2022**, *823*, 153735. [CrossRef]
26. Okoffo, E.D.; Tscharke, B.J.; O'Brien, J.W.; O'Brien, S.; Ribeiro, F.; Burrows, S.D.; Choi, P.M.; Wang, X.; Mueller, J.F.; Thomas, K.V. Release of Plastics to Australian Land from Biosolids End-Use. *Environ. Sci. Technol.* **2020**, *54*, 15132–15141. [CrossRef]
27. Zhang, L.; Xie, Y.; Liu, J.; Zhong, S.; Qian, Y.; Gao, P. An Overlooked Entry Pathway of microplastics into Agricultural Soils from Application of Sludge-Based Fertilizers. *Environ. Sci. Technol.* **2020**, *54*, 4248–4255. [CrossRef]
28. van den Berg, P.; Huerta-Lwanga, E.; Corradini, F.; Geissen, V. Sewage Sludge Application as a Vehicle for microplastics in Eastern Spanish Agricultural Soils. *Environ. Pollut.* **2020**, *261*, 114198. [CrossRef] [PubMed]
29. Corradini, F.; Meza, P.; Eguiluz, R.; Casado, F.; Huerta-Lwanga, E.; Geissen, V. Evidence of Microplastic Accumulation in Agricultural Soils from Sewage Sludge Disposal. *Sci. Total Environ.* **2019**, *671*, 411–420. [CrossRef] [PubMed]
30. Schell, T.; Hurley, R.; Buenaventura, N.T.; Mauri, P.V.; Nizzetto, L.; Rico, A.; Vighi, M. Fate of microplastics in Agricultural Soils Amended with Sewage Sludge: Is Surface Water Runoff a Relevant Environmental Pathway? *Environ. Pollut.* **2022**, *293*, 118520. [CrossRef]
31. Radford, F.; Horton, A.; Hudson, M.; Shaw, P.; Williams, I. Agricultural Soils and microplastics: Are Biosolids the Problem? *Front. Soil Sci.* **2023**, *2*, 941837. [CrossRef]
32. Ziajahromi, S.; Lu, H.-C.; Dwyer, J.; Fernandes, M.; Griffith, M.; Leusch, F.D.L. Transport and Accumulation of microplastics from Biosolids to Australian Agricultural Soils: Detection of microplastics Down to 1 µm. *Environ. Sci. Technol.* **2024**, *58*, 17048–17057. [CrossRef]
33. Samandra, S.; Johnston, J.M.; Jaeger, J.E.; Symons, B.; Xie, S.; Currell, M.; Ellis, A.V.; Clarke, B.O. Microplastic Contamination of an Unconfined Groundwater Aquifer in Victoria, Australia. *Sci. Total Environ.* **2022**, *802*, 149727. [CrossRef] [PubMed]
34. QGIS. QGIS Spatial without Compromise. Available online: https://www.qgis.org/ (accessed on 1 September 2024).
35. Murray-Darling Basin Authority. The Basin. Available online: https://www.mdba.gov.au/basin (accessed on 16 November 2024).
36. Australian Bureau of Statistics. Digital Boundary Files: State Boundaries 2019. Available online: https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026/access-and-downloads/digital-boundary-files#cite-window1 (accessed on 3 August 2024).

37. Department of Industry, Science and Resources. NSW Local Government Areas—Geoscape Administrative Boundaries Datasets. Available online: https://data.gov.au/dataset/ds-dga-f6a00643-1842-48cd-9c2f-df23a3a1dc1e/details?q= (accessed on 4 August 2024).
38. NSW Government—Spatial Services NSW. Water Theme—Hydro Line. Available online: https://portal.spatial.nsw.gov.au/portal/home/item.html?id=7b0e959effd749c788d304a4179abf8a (accessed on 18 August 2024).
39. Murray-Darling Basin Authority. Murray Darling Basin Boundary—Water Act 2007. Available online: https://data.gov.au/data/dataset/murray-darling-basin-boundary (accessed on 3 August 2024).
40. State Government of NSW. NSW Department of Climate Change, Energy, the Environment and Water NSW Landuse 2017—SEED. Available online: https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017 (accessed on 3 August 2024).
41. Australian Bureau of Statistics. Digital Boundary Files: Australia Boundary 2019. Available online: https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026/access-and-downloads/digital-boundary-files#cite-window1 (accessed on 3 August 2024).
42. Reichert, J.; Schellenberg, J.; Schubert, P.; Wilke, T. Responses of Reef Building Corals to Microplastic Exposure. *Environ. Pollut.* **2018**, *237*, 955–960. [CrossRef] [PubMed]
43. Nerland, I.L.; Halsband, C.; Allan, I.; Thomas, K.V. *Microplastics in Marine Environments: Occurrence, Distribution and Effects*; Norwegian Institute for Water Research: Oslo, Norway, 2024; p. 71.
44. Llorca, M.; Schirinzi, G.; Martínez, M.; Barceló, D.; Farré, M. Adsorption of Perfluoroalkyl Substances on microplastics under Environmental Conditions. *Environ. Pollut.* **2018**, *235*, 680–691. [CrossRef]
45. NSW Department of Primary Industries. Landform and Soil Requirements for Biosolids and Effluent Reuse. Available online: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/187627/biosolid-effluent-release.pdf (accessed on 17 August 2024).
46. Terrestrial Ecosystem Research Network (TERN). Soil and Landscape Grid of Australia. Available online: https://esoil.io/TERNLandscapes/Public/Pages/SLGA/ProductDetails-SoilAttributes.html#DataAcknowledgements (accessed on 17 August 2024).
47. Crossman, J.; Hurley, R.R.; Futter, M.; Nizzetto, L. Transfer and Transport of microplastics from Biosolids to Agricultural Soils and the Wider Environment. *Sci. Total Environ.* **2020**, *724*, 138334. [CrossRef] [PubMed]
48. Ding, L.; Zhang, S.; Wang, X.; Yang, X.; Zhang, C.; Qi, Y.; Guo, X. The Occurrence and Distribution Characteristics of microplastics in the Agricultural Soils of Shaanxi Province, in North-Western China. *Sci. Total Environ.* **2020**, *720*, 137525. [CrossRef]
49. Bureau of Meteorology. Rainfall—Climate Averages Maps. Available online: http://www.bom.gov.au/climate/maps/averages/rainfall/ (accessed on 10 August 2024).
50. State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water. NSW Aridity Index—High Resolution (30 Meter)—SEED. Available online: https://datasets.seed.nsw.gov.au/dataset/nsw-aridity-index-high-resolution-30-meter (accessed on 24 August 2024).
51. Nyman, P.; Sherwin, C.; Langhans, C.; Lane, P.; Sheridan, G. Downscaling Regional Climate Data to Calculate the Radiative Index of Dryness in Complex Terrain. *Aust. Meteorol. Oceanogr. J.* **2014**, *64*, 109–122. [CrossRef]
52. Zubris, K.A.V.; Richards, B.K. Synthetic Fibers as an Indicator of Land Application of Sludge. *Environ. Pollut.* **2005**, *138*, 201–211. [CrossRef]
53. Palazot, M.; Soccalingame, L.; Froger, C.; Jolivet, C.; Bispo, A.; Kedzierski, M.; Bruzaud, S. First National Reference of Microplastic Contamination of French Soils. *Sci. Total Environ.* **2024**, *918*, 170564. [CrossRef] [PubMed]
54. Chu, X.; Li, T.; Li, Z.; Yan, A.; Shen, C. Transport of Microplastic Particles in Saturated Porous Media. *Water* **2019**, *11*, 2474. [CrossRef]
55. Li, M.; Zhang, X.; Yi, K.; He, L.; Han, P.; Tong, M. Transport and Deposition of Microplastic Particles in Saturated Porous Media: Co-Effects of Clay Particles and Natural Organic Matter. *Environ. Pollut.* **2021**, *287*, 117585. [CrossRef]
56. Wang, Y.; Xu, L.; Chen, H.; Zhang, M. Retention and Transport Behavior of Microplastic Particles in Water-Saturated Porous Media. *Sci. Total Environ.* **2022**, *808*, 152154. [CrossRef] [PubMed]
57. US EPA. Ionic Strength. Available online: https://www.epa.gov/caddis/ionic-strength (accessed on 1 September 2024).
58. State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water. NSW State-Wide Hydrogeological Landscapes 2020 (First Edition)—SEED. Available online: https://datasets.seed.nsw.gov.au/dataset/nsw-state-wide-hydrogeological-landscapes-2020-first-edition (accessed on 1 September 2024).
59. Jeong, E.; Kim, Y.-I.; Lee, J.-Y.; Raza, M. Microplastic Contamination in Groundwater of Rural Area, Eastern Part of Korea. *Sci. Total Environ.* **2023**, *895*, 165006. [CrossRef]
60. Bureau of Meteorology. National Groundwater Information System. Available online: https://data.gov.au/data/dataset/national-groundwater-information-system (accessed on 24 August 2024).
61. O'Connor, D.; Pan, S.; Shen, Z.; Song, Y.; Jin, Y.; Wu, W.-M.; Hou, D. Microplastics Undergo Accelerated Vertical Migration in Sand Soil Due to Small Size and Wet-Dry Cycles. *Environ. Pollut.* **2019**, *249*, 527–534. [CrossRef]

62. Lincmaierová, K.; Botyanszká, L.; Lichner, L.; Toková, L.; Zafeiriou, I.; Bondarev, D.; Horák, J.; Šurda, P. Assessing Microplastic-Induced Changes in Sandy Soil Properties and Crop Growth. *Agriengineering* **2023**, *5*, 1555–1567. [CrossRef]
63. Blanda, V.; Blanda, M.; Russa, F.; Scimeca, R.; Scimeca, S.; D'Agostino, R.; Auteri, M.; Torina, A. Geo-Statistical Analysis of *Culicoides* spp. Distribution and Abundance in Sicily, Italy. *Parasites Vectors* **2018**, *11*, 78. [CrossRef]