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Application of spatial statistics as a screening tool for sustainable flood retention basin management

Qinli Yang[1], Miklas Scholz, FCIWEM[1,2] & Junming Shao[3]

[1]Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, Edinburgh, UK; [2]Civil Engineering Research Group, School of Computing, Science and Engineering, The University of Salford, Salford, UK; and [3]Institute of Computer Science, Database and Information Systems, Ludwig-Maximilian University of Munich, Munich, Germany

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Correspondence
Prof. Miklas Scholz, Chair in Civil Engineering, Civil Engineering Research Group, School of Computing, Science and Engineering, The University of Salford, Newton Building, Salford, Greater Manchester M5 4WT, United Kingdom.
Email: m.scholz@salford.ac.uk

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Abstract

In the context of climate change and the EU flood directive, this paper analyses and explores sustainable flood retention basins (SFRB) as adaptive structures contributing to water resources management and flood risk control. A dataset of 371 potential SFRB (including many operating reservoirs) characterized by 40 variables have been surveyed across central Scotland. However, the spatial properties of these SFRB, such as water storage (which relates to flooding depth) in different regions, are ambiguous. This paper uses geostatistics on the Scottish dataset. Spatial analysis showed that ordinary kriging, which is a spatial interpolation method, could be successfully applied to estimate numerical values for all key flood control variables everywhere in the study area. Moreover, the probability that certain threshold values relevant to flood control managers were exceeded can also be calculated by using disjunctive kriging. The findings provide an effective screening tool in assessing flood control using SFRB.

Introduction

The European Union has introduced the Flood Directive 2007/60 EC (EU 2007), which requires each member state to develop flood risk management plans and flood defences. The concept of sustainability has only recently been applied to flood defences, implying that all available infrastructures should be reassessed (Shih & Nicholls 2007). An assessment system that can be applied economically to a wide range of water bodies, wetlands and artificial impoundments would be of value in implementing the flood directive (EU 2007).

An SFRB is defined as an impoundment or wetland which has a predefined or potential role in flood defence and diffuse pollution control that can be accomplished cost effectively through best management practice, achieving sustainable flood risk management and enhancing sustainable drainage, pollution reduction, biodiversity, green space and recreational opportunities for society. The word sustainable in SFRB means capable of being maintained at a steady level without exhausting natural resources, harming the environment or causing severe ecological damage (Mcminn *et al*. 2010). To represent diverse functions of SFRB, six types of SFRB were named as follows (Scholz 2007; Scholz & Sadowski 2009): Hydraulic Flood Retention Basin (type 1), Traditional Flood Retention Basin (type 2), Sustainable Flood Retention Wetland (type 3), Aesthetic Flood Treatment Wetland (type 4), Integrated Flood Retention Wetland (type 5) and Natural Flood Retention Wetland (type 6).

Kriging is a group of geostatistical techniques designed to interpolate the value of a random field at an unobserved location derived from studies of its value at nearby sites. The spatial variation of a variable is quantified by a semivariogram, which is a graph describing the characteristics of a regionalized variable (Rivoirard 1994). Various kriging techniques have also been applied successfully in hydrogeology and remote sensing (Webster & Oliver 2001), natural resource management (Oliver *et al*. 1996), environmental science (Rivoirard 1994) and agriculture (Liu *et al*. 2006). More recently, geostatistics has been applied in the wider area of water resource management, for example floodplain soil property mapping (Gallardo 2003), river water quality monitoring (Karamouz *et al*. 2009) and river network discharge mapping (Sauquet 2006). An effective and rapid geostatistical tool providing examples of flood management involving SFRB, which are characterized by clear and relevant characterization variables, would support planning and communication among practitioners and planners.

The aim of this research paper is to assess the potential role of SFRB in flood risk management with the help of geostatistical tools to improve communication between stakeholders. The key objectives are as follows:

- to spatially analyse all relevant SFRB characterization variables which could be used to assess flood control options;
- to assess attributes at unobserved sites using ordinary kriging with the support of a large and detailed example case study dataset; and
- to apply disjunctive kriging to assess the probability for individual variables to exceed specific management thresholds relevant for flood control.

The authors would like to highlight that this is a multi-disciplinary study applying geostatistics as a screening tool in the area of water research, and that it is not intended to necessarily replace other studies such as hydrological models.

Methodology

Data acquisition

The survey of any SFRB is a two-stage process combining a desk study and a field visit during which 40 variables (see Table 1) are assessed (McMinn *et al*. 2010). A guidance manual used to determine the 40 variables characterizing water bodies including SFRB has been published by Scholz & Yang (2010). The variables include conventional hard engineering attributes such as Dam Length and Dam Height, together with more holistic attributes such as how Engineered the structure appears (McMinn *et al*. 2010; Scholz & Yang 2010).

A dataset of 371 SFRB sites, which are located in the wider central Scotland area (Fig. 1), has been developed. Figure 1 shows the locations of the different SFRB types. Each SFRB site is associated with 40 variables. At least 100 sites are required to produce reliable maps based on stable variograms (Webster & Oliver 2001). Thus, the selected number of sites is sufficient to apply geostatistical methods such as kriging.

In this paper, the authors only focus on flood-related variables such as Engineered (relative value, expressed in %, based on expert judgement of how engineered a basin appears in contrast to a natural water body), Mean Flooding Depth (average depth within the basin during flooding), Maximum Flood Water Volume (maximum volume of water within a basin during a typical flood) as discussed by Scholz (2007), McMinn *et al*. (2010) and Scholz & Yang (2010), and two compound variables: Managed Mean Flooding Depth and Managed Maximum Flood Water Volume. The first compound variable can be derived from the variables Mean Flooding Depth and Mean Depth of the Basin. Managed Mean Flooding Depth data for drinking water reservoirs are similar to the values collected for Mean Flooding Depth, while values for lakes are calculated by subtracting Mean Depth of the Basin from Mean Flooding Depth. The second compound variable Managed

Table 1 Classification variables used for the assessment of sustainable flood retention basins

ID	Variable and unit	ID	Variable and unit
1	Engineered (%)	21	Impermeable Soil Proportion (%)
2	Dam Height (m)	22	Seasonal Influence (%)
3	Dam Length (m)	23	Site Elevation (m)
4	Outlet Arrangement and Operation (%)	24	Vegetation Cover (%)
5	Aquatic Animal Passage (%)	25	Algal Cover in Summer (%)
6	Land Animal Passage (%)	26	Relative Total Pollution (%)
7	Floodplain Elevation (m)	27	Mean Sediment Depth (cm)
8	Basin and Channel Connectivity (m)	28	Organic Sediment Proportion (%)
9	Wetness (%)	29	Flotsam Cover (%)
10	Proportion of Flow within Channel (%)	30	Catchment Size (km^2)
11	Mean Flooding Depth (m)	31	Urban Catchment Proportion (%)
12	Typical Wetness Duration (d/a)	32	Arable Catchment Proportion (%)
13	Estimated Flood Duration (d/a)	33	Pasture Catchment Proportion (%)
14	Basin Bed Gradient (%)	34	Viniculture Catchment Proportion (%)
15	Mean Basin Flood Velocity (cm/s)	35	Forest Catchment Proportion (%)
16	Wetted Perimeter (m)	36	Natural Catchment Proportion (%)
17	Maximum Flood Water Volume (m^3)	37	Groundwater Infiltration (%)
18	Flood Water Surface Area (m^2)	38	Mean Depth of the Basin (m)
19	Mean Annual Rainfall (mm)	39	Length of Basin (m)
20	Drainage (cm/day)	40	Width of Basin (m)

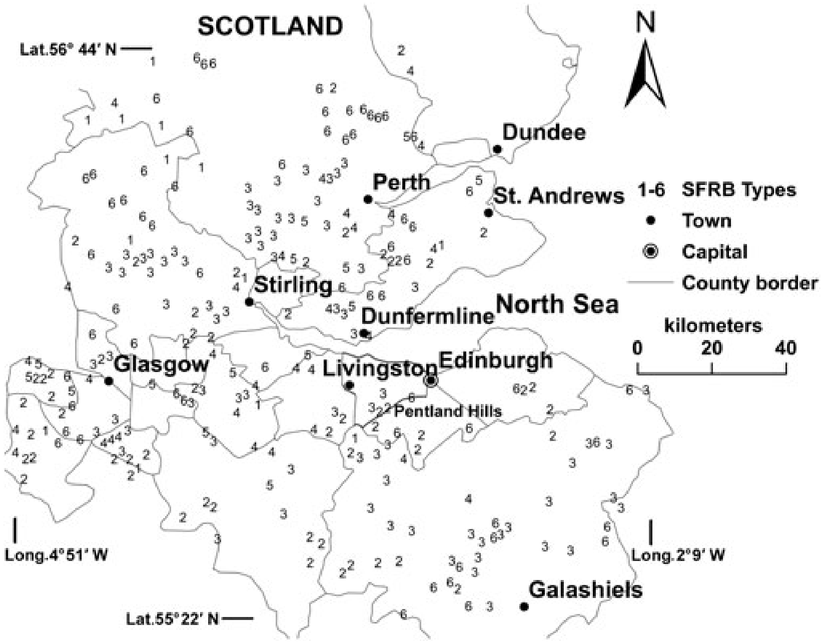

Fig. 1. Study area, administrative boundaries and the 371 identified sustainable flood retention basin (SFRB) types in the wider central Scotland area (UK).

Maximum Flood Water Volume is derived by multiplying Managed Mean Flooding Depth by Flood Water Surface Area. For details on how to define and determine the values for the variables, readers may refer to Scholz & Yang (2010).

Table 2 shows the summary statistics of the original values for the variables Engineered, Mean Flooding Depth, Managed Mean Flooding Depth, Maximum Flood Water Volume and Managed Maximum Flood Water Volume determined for the Scottish SFRB dataset. The data variability for most variables is relatively high, reflecting the diversity of SFRB. The high variability of Managed Maximum Flood Water Volume is likely to negatively influence the prediction errors of kriged maps.

Table 2 Summary statistics of the Scottish original quality-controlled values for the variables Engineered (E, %), Mean Flooding Depth (MFD, m), Managed Mean Flooding Depth (MMFD, m), Maximum Flood Water Volume (MFWV, m^3), and Managed Maximum Flood Water Volume (MMFWV, m^3)

Statistic	E	MFD	MMFD	MFWV	MMFWV
Minimum	0	1	0	2450	0
Maximum	100	70	42	$260\,000 \times 10^4$	$14\,200 \times 10^4$
Mean	40.5	6.9	4.5	2312×10^4	462×10^4
Standard deviation	33.52	8.13	6.01	$18\,801 \times 10^4$	1589×10^4

The number of samples was 371.

Variogram analysis

In geostatistics, the variogram is a function describing the degree of spatial statistical dependence of a spatial random field (called spatial autocorrelation). A variogram interpolates a raster from a set of points using kriging with a known semivariogram model and its parameters (Rivoirard 1994). The experimental variogram can be computed by using Eq. (1).

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\{z(x_i) - z(x_i + h)\}^2, \quad (1)$$

where $\gamma(h)$ is the sample semivariance at lag h, which is a vector in both distance and direction, $z(x_i)$ and $z(x_i{+}h)$ are the values of $Z(x)$ at locations x and $x{+}h$, respectively, and n is the number of pairs of comparisons separated by a lag h for $i = 1, 2, \ldots, n$.

The parameters used to describe variograms are nugget, partial sill and range. The parameter nugget is the height of the jump of the semivariogram at the discontinuity at the origin. Sill is the limit of the variogram tending to infinity lag distance, while the range is the distance in which the difference of the variogram from the sill becomes negligible. And a partial sill is the sill minus the nugget.

The empirical variogram, which provides information on the spatial autocorrelation of the SFRB dataset, is fitted by a mathematical function, which describes the structure of variation and ensures validity of the variogram. Before the production of any kriged map, the most suitable model was fitted by applying the least squares method to the points forming the empirical semivariogram.

Ordinary kriging

The key application of kriging in flood management with SFRB is the prediction of attribute values at unknown locations. Kriging forms weights from a semivariogram based on surrounding measured values to predict figures for unmeasured sites. The measured values nearest to the unmeasured sites have the greatest influence. Predictions were made for each location in the wider central Scotland area based on the semivariogram and the spatial arrangement of measured values that are located within the vicinity.

Ordinary kriging provides best linear unbiased estimations with minimum error variance and is the most commonly used type of kriging. Furthermore, kriging weighs the surrounding measured values to derive a prediction for an unmeasured location. The general formula is formed as a weighted sum of the data [Eq. (2)]. The weight λ_i depends on a fitted model to the measured points, the distance to the prediction location, and the spatial relationships among the measured values around the prediction location.

$$Z(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i), \quad (2)$$

where $Z(S_i)$ denotes the measured value at the *i*th location, λ_i is an unknown weight for the measured value at the *i*th location, S_0 is the prediction location, and N means the number of measured values.

Disjunctive kriging

Disjunctive kriging is a nonlinear generalization of kriging. This estimation technique allows for the conditional probability that the value of a spatially variable SFRB characterization parameter is greater than a cut-off level yet to be calculated (Rivoirard 1994; Liu *et al*. 2006). The method can be used in flood risk management decision making to help determine when some action, such as the construction of a new SFRB or a change in reservoir management, is necessary. Two input parameters are required to use the technique: a cut-off level and the critical probability level (Oliver *et al*. 1996). The relevant standard formulae for disjunctive kriging are shown in Eqs. (3) to (5). Sample values x in the original space A are transformed into y in a normal space B that has a standard normal distribution such that $x=\varphi(y)$. The function φ is written as a linear combination of Hermite polynomials as shown in Eq. (3) and discussed by Grad (2006).

$$\varphi(y) = \sum_{k=0}^{\infty} C_k H_k(y), \quad (3)$$

where $\varphi(y)$ is the function of a linear combination of Hermite polynomials, C_k are coefficients to be calculated from the sample values x_i ($i=1, 2, \ldots, n$), and $H_k(y)$ is a Hermite polynomial of the order k.

In the space B, the value y has the so-called coordinates $H_0(y), H_1(y), \ldots, H_k(y), \ldots$, while in the space A, the corresponding value $x=\varphi(y)$ has the coordinates $C_0H_0(y)$, $C_1H_1(y), \ldots, C_kH_k(y), \ldots$. Each sample value x_i is transformed to a value y_i ($i=1, 2, \ldots, n$) with coordinates $H_0(y_i), H_1(y_i), \ldots, H_k(y_i), \ldots$. To obtain the disjunctive kriging estimate μ_D^*, which belongs to the space A, someone first calculates the corresponding value υ_D^*in the space B. If $H_{0\upsilon}^*$, $H_{1\upsilon}^*$, …, $H_{k\upsilon}^*$, …, are the coordinates of υ_D^* in B, these coordinates are obtained by a linear combination of the corresponding coordinates of the sample values. The estimator $H_{k\upsilon}$ is of the form shown in Eq. (4). To obtain μ_D^* from υ_D^*, the function φ is used as shown in Eq. (5).

$$H_{kv} = \sum_{i=1}^{n} b_i H_k(y_i) \quad (4)$$

where H_{kv} is the coordinate of the normalized block estimator v_D in space B, calculated from the surrounding sample values y_i ($i=1, 2, \ldots, n$), and b_i are weights, optimally defined through the use of the autocorrelation function of the sample values.

$$\mu_D = \varphi(\upsilon_D) = \sum_{k=0}^{\infty} C_k H_{kv} \quad (5)$$

where μ_D represents the disjunctive kriging estimator, and v_D is the corresponding value in normalized space B.

The geostatistical analysis was performed within the ArcGIS 9.2 software environment (Liu *et al*. 2006).

Results and discussion

Findings based on ordinary kriging

Ordinary kriging was applied for the key flood control variables Engineered, Mean Flooding Depth, Managed Mean Flooding Depth, Maximum Flood Water Volume and Managed Maximum Flood Water Volume. The statistics of these target variables are summarized in Table 2. The high variance of these variables reflects the diverse types of SFRB. Table 3 presents the ordinary kriging characteristics for these variables.

Figure 2(a)–(e) show map examples applying ordinary kriging for the variables Engineered, Mean Flooding Depth, Managed Mean Flooding Depth, Maximum Flood

Table 3 Summary of ordinary kriging characteristics for the variables Engineered (E, %), Mean Flooding Depth (MFD, m), Managed Mean Flooding Depth (MMFD, m), Maximum Flood Water Volume (MFWV, m^3), and Managed Maximum Flood Water Volume (MMFWV, m^3)

Variogram and error	Parameters	E	MFD	MMFD	MFWV	MMFWV
Variogram	Model	Exponential	Gaussian	Spherical	Spherical	Gaussian
	Range	125 534	69 788	96 548	167 522	167 522
	Partial sill	255.04	52.19	24.30	3.6297×10^{16}	2.5236×10^{14}
	Nugget	953.06	25.26	17.59	1.5532×10^{16}	1.5356×10^{4}
Mean standardized error for prediction		−0.0018	−0.0103	−0.0036	0.0044	0.0072

The number of samples was 371. Variograms: no data transformation.

Water Volume and Managed Maximum Flood Water Volume respectively. High numerical values for the variable Engineered generally indicate the likely necessity for high civil engineering investment to be made when planning for the construction of a new SFRB (Fig. 2a). The most engineered SFRB structures are likely to be found in the south-west of the study area, which coincides with the highest density of reservoirs and lakes used for water supply purposes. In contrast, for the study area in the north, relatively low investment for flood infrastructure is required. This variable is particularly useful when a decision has to be made on where old flood infrastructure needs to be upgraded or new SFRB constructed. It would be preferable to have areas prone to flooding being located within catchments associated with low values for the variable Engineered and high values for those such as Managed Mean Flooding Depth and Managed Maximum Flood Water Volume.

The spatial distribution for the variables Mean Flooding Depth and Managed Mean Flooding Depth are shown in Fig. 2(b) and (c), respectively. The Mean Flooding Depth is relatively high in the less populated upland areas of the north-west and south of the study area as well as within the Pentland Hills, a small area directly located south-west of Edinburgh (Fig. 1). Low values for the variable Mean Flooding Depth are rare and patchy.

In comparison, the Managed Mean Flooding Depth variable is high only in the north-east and south-west of the study area. Moreover, high values have also been noted for some parts of the Pentland Hills. The area situated to the south-west of Edinburgh also has the highest density of reservoirs that could be used for hydraulic purposes such as flood control to protect the capital. The south-east and north-central regions are dominated by low flooding depths. The comparison indicates that the new variable Managed Mean Flooding Depth has much lower values than the old variable Mean Flooding Depths, because the permanent water contained in lakes has not been taken into account when calculating the former variable. The new variable is therefore a much better indicator for high flood control potential.

Figure 2(d) and (e) show the most likely values for the variables Maximum Flood Water Volume and Managed Maximum Flood Water Volume. These volume-based variables mirror the depth-based variables, indicating that higher depths relate to higher volumes, which is particularly the case for upland areas far away from major urban settlements.

Ordinary kriging has proved to be ideal for more than 90% of the SFRB ground surveys, because it results in maps which are easy to understand for practitioners (e.g. Fig. 2). Maps appear to be smooth because most short-range noise was removed during kriging, which allows the flood risk manager to identify the key underlying patterns within complex data structures.

Findings based on disjunctive kriging

The maps produced with ordinary kriging assist flood risk managers in identifying areas of low or high values for various SFRB variables. However, these maps should not be taken at face value since many are misleading to a greater or lesser extent. It is therefore necessary to use a technique such as disjunctive kriging, which provides estimates of the probability based on data given that the true values exceed a threshold at an unsampled location. It is necessary to perform a lognormal transformation for some variables in order not to violate underlying assumptions for disjunctive kriging.

Table 4 shows a summary of disjunctive kriging parameters for the key flood control variables Engineered, Mean Flooding Depth, Managed Mean Flooding Depth, Maximum Flood Water Volume and Managed Maximum Flood Water Volume. Based on data properties and expert judgment, the thresholds for the variable Engineered and any variables indicating flooding depth and flood water volume were set as 30%, 3 m and 350 000 m^3, respectively. Similar to ordinary kriging, the model that led to minimum mean standardized error was selected as the most suitable model fitting the variables.

Map examples showing the application of disjunctive kriging for the key variables are summarized in Fig. 3(a)–(e). Areas of low and high probabilities for the variable Engineered are relatively small and patchy (Fig. 3a). The probability map shown in Fig. 3(a) can be used in conjunction with Fig. 2(a) and all maps indicating

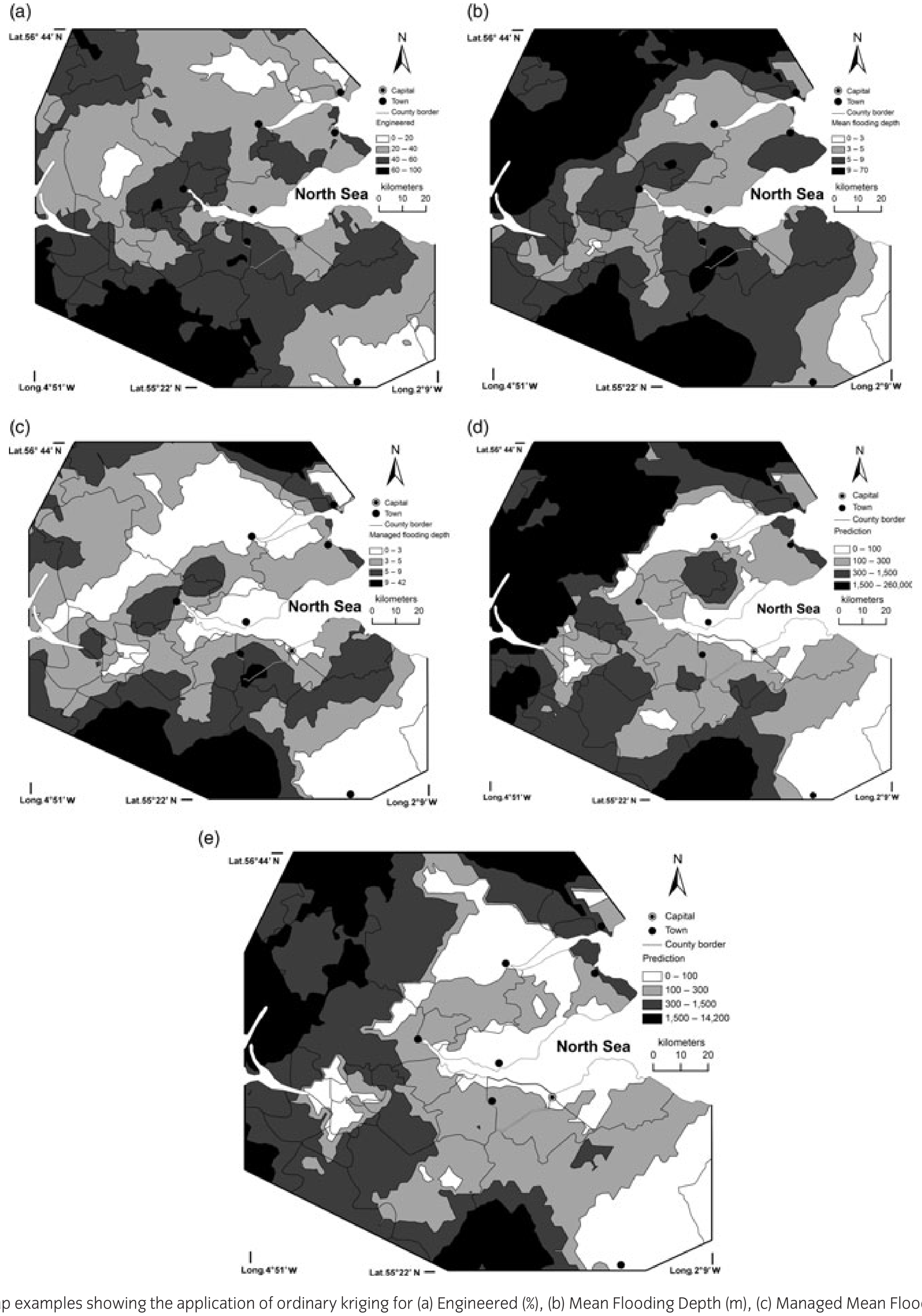

Fig. 2. Map examples showing the application of ordinary kriging for (a) Engineered (%), (b) Mean Flooding Depth (m), (c) Managed Mean Flooding Depth (m), (d) Maximum Flood Water Volume (m^3) and (e) Managed Maximum Flood Water Volume (m^3).

flooding depth and flood water volume to determine the areas of greatest investment potential if flooding is likely to be a problem.

The maps showing probabilities of exceeding 3 m flooding depth associated with the variables Mean Flooding Depth and Managed Mean Flooding Depth should be

Table 4 Summary of disjunctive kriging characteristics for the variables Engineered (E, %), Mean Flooding Depth (MFD, m), Managed Mean Flooding Depth (MMFD, m), Maximum Flood Water Volume (MFWV, m^3), and Managed Maximum Flood Water Volume (MMFWV, m^3)

Variogram, thresholds and error	Parameters	E	MFD	MMFD	MFWV	MMFWV
Variogram	Transformation	Normal score	None	Normal score	Log	Normal score
	Model	Exponential	Exponential	Spherical	Spherical	Spherical
	Range	16 663	34 300	15 806	61 058	37 555
	Partial sill	0.32	15.16	0.41	0.79	0.22
	Nugget	0.61	50.83	0.48	4.36	0.74
Primary threshold for disjunctive kriging	30	3	3	350 000	350 000	
Mean standardized error for estimation		0.0173	0.0422	0.0351	0.0988	− 0.0098

The number of samples was 371.

used to estimate the likely return in flood infrastructure investment throughout the study area (Fig. 3b and c). The higher the probability, the more likely it is that an existing or planned SFRB is making a positive impact on flood control. In contrast to the Mean Flooding Depth, the map for Managed Mean Flooding Depth indicates much lower probability values. Moreover, only those areas that are dominated by reservoirs which could be used by Scottish Water and local authorities for flood control management are shown. The greatest potential for active flood control is in areas situated to the south-west of the capital such as the Pentland Hills.

Figure 3(d) and (e) show that the areas with the greatest flood storage capacity are located in upland catchments distant from populated lowland areas. The probabilities for the likely volumes that could be used for active flood control management by Scottish Water and local authorities are clearly shown in Fig. 3(e), because unmanageable storage volumes within natural water bodies have been excluded from the probability map. A comparison of Fig. 3(a) and (e) indicates that the north-west of the study area has the greatest potential for low-cost SFRB investment yielding a high flood water storage volume return.

Consequences for flood risk management in Scotland

Traditional Flood Retention Basins (SFRB type 2) and Natural Flood Retention Wetlands (SFRB type 6) dominate the wider central Scotland area (McMinn *et al*. 2010). Figure 4 shows an example of a Traditional Flood Retention Basin that is, however, currently only used for drinking water supply purposes. There is great underutilized potential in using former and less important current potable water supply reservoirs for flood control purposes. In comparison, Fig. 5 is a representative example of a Natural Flood Retention Wetland which is predominantly used for environmental protection and recreational purposes, and has limited flood control potential.

The fieldwork program identified a large number of former water supply reservoirs, which were predominantly identified as SFRB type 2. In the vast majority of cases, these structures now fulfil multiple roles providing opportunities for recreation, nature conservation and angling with many former drinking water reservoirs or industrial water supply structures being managed as fisheries.

A feature of these sites, based on the majority of current (SFRB type 1) and former (SFRB type 2; Fig. 4) drinking water supply reservoirs surveyed, is that they are maintained at their maximum water retention volumes, and their corresponding spillways are continuously in operation. In this mode of operation, the extensive infrastructure is making very little contribution to water retention (i.e. flood control) in the upper catchments.

The proposed methodology could be used directly for planning purposes by classifying water bodies into SFRB types. For example, the SFRB concept could support the Water of Leith (located in the Pentland Hills) Flood Prevention Scheme to protect Edinburgh from flooding (Scottish Government 2010). A proper classification of the water bodies located within the Water of Leith catchment area that have flood control potential would clarify their individual planning status. Clarification of their current purpose (e.g. water supply, flood attenuation, recreation and/or environmental protection) would benefit communication between all stakeholders (e.g. local authorities, land owners and Scottish Water) involved with this case study to optimize their planning effort.

It follows that a change in management practice of reservoir-like structures by Scottish Water and local authorities could assist in sustainable flood risk management planning, leading to more sustainable reservoirs (SFRB type 3). Effectively, this would require some water to be released from the reservoirs before expected heavy precipitation. As the vast majority of former drinking

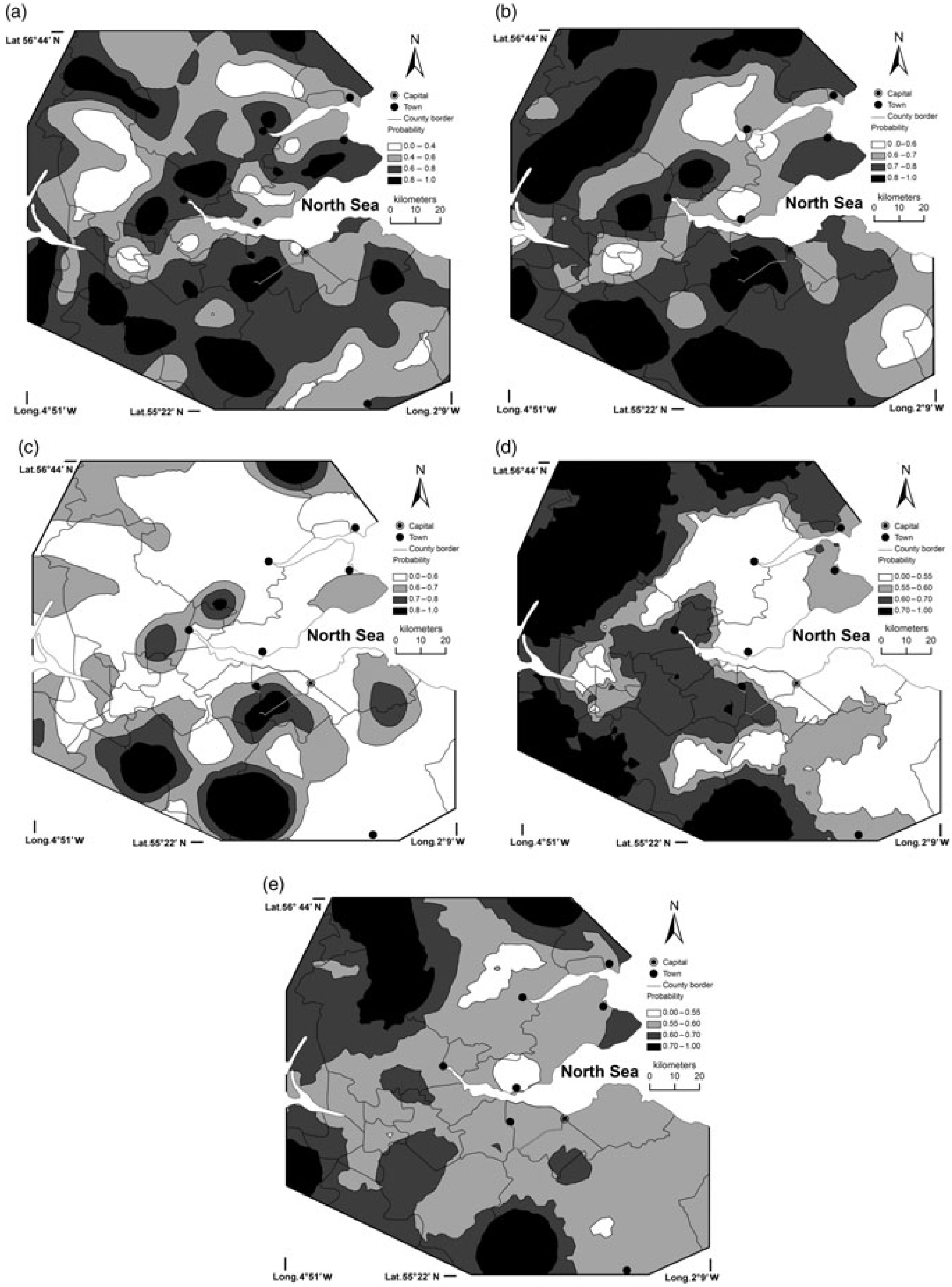

Fig. 3. Map examples showing the application of disjunctive kriging for (a) Engineered (%; exceeding 30%), (b) Mean Flooding Depth (m, exceeding 3 m), (c) Managed Mean Flooding Depth (m, exceeding 3 m), and (d) Maximum Flood Water Volume (m^3, exceeding $35 \times 10^4\,m^3$), and (e) Managed Maximum Flood Water Volume (m^3, exceeding $35 \times 10^4\,m^3$).

Fig. 4. Glenfarg Reservoir (near to Rossie Ochill, County of Perth and Kinross), an example of a Traditional Flood Retention Basin (type 2) that is, however, currently used only for drinking water supply purposes (picture taken by Qinli Yang on 20 November 2008).

Fig. 5. Hare Myre (2.5 km suth-east of Blairgowrie, County of Perth and Kinross), an example of a Natural Flood Retention Wetland (type 6) that is predominantly used for environmental protection, recreational and diffuse pollution control purposes (picture taken by Qinli Yang on 7 July 2009).

water reservoirs have manual water level control, this would require on-site visits to manually release excess water, only closing the reservoir before a heavy rainfall event. This simple operation would enhance the reservoir capacity for water storage in the upper reach of the catchment and retard the peak flows from the upper catchment, which is likely to lead to a reduction of flooding downstream. Moreover, a geostatistical approach to river network management, already attempted in France (Sauquet 2006) and Iran (Karamouz *et al*. 2009), may also benefit flood risk management planning in Scotland.

Conclusions

(1) For the first time, the geostatistical analysis techniques of ordinary kriging and disjunctive kriging were successfully applied to SFRB management in the context of flood control. This novel approach provides efficient and rapid predictions relevant to flood management with respect to large areas comprising sites that have not been surveyed. The proposed geostatistical methodology will aid stakeholder communication by delivering information regarding the most favourable locations for SFRB development.

(2) Traditional Flood Retention Basins consisting predominantly of former drinking water reservoirs are clearly a noticeable component of the Scottish landscape. These structures could be used for low-cost flood control purposes if their water levels were actively controlled on a seasonal basis.

(3) The key flood control variables are Engineered, Mean Flooding Depth, Maximum Flood Water Volume, Managed Mean Flooding Depth and Managed Maximum Flood Water Volume. The latter two compound variables are novel and essential in identifying the underutilized flood control potential of former and current water supply reservoirs.

(4) The spatial flood control assessment methodology ordinary kriging allowed for a clear interpretation of areas requiring further flood control investment.

(5) Disjunctive kriging was successfully used to assess the probability of individual variables to exceed specific management thresholds, which are relevant for flood control.

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