

Package ‘OCNet’

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Title Optimal Channel Networks

Version 0.2.0

Description Generate and analyze Optimal Channel Networks (OCNs): oriented spanning trees reproducing all scaling features characteristic of real, natural river networks. As such, they can be used in a variety of numerical experiments in the fields of hydrology, ecology and epidemiology. See Carraro et al. (2020) <doi:10.1101/2020.02.17.948851> for a presentation of the package; Rinaldo et al. (2014) <doi:10.1073/pnas.1322700111> for a theoretical overview on the OCN concept; Furrer and Sain (2010) <doi:10.18637/jss.v036.i10> for the construct used.

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OCNet-package

Create and analyze Optimal Channel Networks.

Description

A package that allows the generation and analysis of synthetic river network analogues, called Optimal Channel Networks (OCNs).

References

Rinaldo, A., Rigon, R., Banavar, J. R., Maritan, A., & Rodriguez-Iturbe, I. (2014). Evolution and selection of river networks: Statics, dynamics, and complexity. *Proceedings of the National Academy of Sciences of the United States of America*, 111(7), 2417-2424. doi:10.1073/pnas.1322700111

Carraro et al.

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See Also

`vignette("OCNet")`

 aggregate_OCN

Aggregate an Optimal Channel Network

Description

Function that, given an OCN, builds the network at the river network (RN), aggregated (AG), sub-catchment (SC), and catchment (CM) levels.

Usage

```
aggregate_OCN(OCN, thrA = 0.002 * OCN$dimX * OCN$dimY *
  OCN$cellsize^2, streamOrderType = "Strahler", maxReachLength = Inf)
```

Arguments

OCN	List as produced by landscape_OCN .
thrA	Threshold value on drainage area used to derive the aggregated network. If thrA = 0, no aggregation is performed: every FD node is also a node at the RN and AG levels. In this case, the function aggregate_OCN can still be used to compute statistics such as OCN\$AG\$streamOrder.
streamOrderType	If "Strahler", Strahler stream order is computed; if "Shreve", Shreve stream order is computed.
maxReachLength	Maximum reach length allowed (in planar units). If the path length between a channel head and the downstream confluence is higher than maxReachLength, the reach starting from the channel head will have a length up to maxReachLength, while the next downstream pixel is considered as a new channel head, from which a new reach departs.

Details

Note that each node (and the corresponding edge exiting from it, in the case of non-outlet nodes) at the AG level corresponds to a subcatchment at the SC level that shares the same index: for instance, SC\$toFD[i] contains all elements of AG\$toFD[i] (that is, the indices of pixels at FD level that constitute the edge departing from node i are also part of subcatchment i).

Value

A list that contains all objects contained in OCN, in addition to the objects listed below. New sublists RN, AG, SC, containing variables at the corresponding aggregation levels, are created. Refer to section 4.2 of the [vignette](#) for a more detailed explanation on values OCN\$XX\$toYY, where XX and YY are two random aggregation levels.

FD\$toRN	Vector (of length OCN\$FD\$nNodes) whose values are equal to 0 if the FD node is not a node at the RN level. If FD\$toRN[i] != 0, then FD\$toRN[i] is the index at the RN level of the node whose index at the FD level is i. Thereby, FD\$toRN[i] = j implies RN\$toFD[j] = i.
FD\$toSC	Vector (of length OCN\$FD\$nNodes) of SC indices for all nodes at the FD level. If OCN\$FD\$toSC[i] = j, then i %in% OCN\$SC\$toFD[[j]] = TRUE.
RN\$A	Vector (of length RN\$nNodes) containing drainage area values for all RN nodes (in square planar units).
RN\$W	Adjacency matrix (RN\$nNodes by RN\$nNodes) at the RN level. It is a spam object.
RN\$downNode	Vector (of length RN\$nNodes) representing the adjacency matrix at RN level in a vector form: if RN\$downNode[i] = j then RN\$W[i, j] = 1. If o is the outlet node, then RN\$downNode[o] = 0.
RN\$drainageDensity	Drainage density of the river network, calculated as total length of the river network divided by area of the lattice. It is expressed in planar units ⁽⁻¹⁾ .
RN\$leng	Vector (of length RN\$nNodes) of lengths of edges departing from nodes at the RN level. Its values are equal to either 0 (if the corresponding node is an outlet), OCN\$cellsize (if the corresponding flow direction is horizontal/vertical), or sqrt(2)*OCN\$cellsize (diagonal flow).
RN\$nNodes	Number of nodes at the RN level.
RN\$nUpstream	Vector (of length RN\$nNodes) providing the number of nodes upstream of each node (the node itself is included).
RN\$outlet	Vector (of length OCN\$FD\$nOutlet) indices of nodes at RN level corresponding to outlets.
RN\$Slope	Vector (of length RN\$nNodes) of pixel slopes at RN level.
RN\$toAG	Vector (of length RN\$nNodes) whose values are equal to 0 if the RN node is not a node at the AG level. If RN\$toAG[i] != 0, then RN\$toAG[i] is the index at the AG level of the node whose index at the RN level is i. Thereby, RN\$toAG[i] = j implies AG\$toRN[j] = i.
RN\$toAGReach	Vector (of length RN\$nNodes) identifying to which edge (reach) the RN nodes belong. If RN\$toAGReach[i] = j, the RN node i belongs to the edge departing from from the AG node j (which implies that it may correspond to the AG node j itself.)
RN\$toFD	Vector (of length RN\$nNodes) with indices at FD level of nodes belonging to RN level. RN\$toFD[i] = j implies OCN\$FD\$toRN[j] = i.
RN\$toCM	Vector (of length RN\$nNodes) with catchment index values for each RN node. Example: RN\$toCM[i] = j if node i drains into the outlet whose location is defined by outletSide[j], outletPos[j].
RN\$upstream	List (of length RN\$nNodes) whose object i is a vector (of length RN\$nUpstream[i]) containing the indices of nodes upstream of a node i (including i).
RN\$X, RN\$Y	Vectors (of length RN\$nNodes) of X, Y coordinates of nodes at RN level.
RN\$Z	Vector (of length RN\$nNodes) of Z coordinates of nodes at RN level.

AG\$A	Vector (of length AG\$nNodes) containing drainage area values for all nodes at AG level. If i is a channel head, then $AG\$A[RN\$toAG[i]] = RN\$A[i]$.
AG\$AReach	Vector (of length AG\$nNodes) containing drainage area values computed by accounting for the areas drained by edges departing from AG nodes. In other words, $AG\$AReach[i]$ is equal to the drainage area of the last downstream node belonging to the reach that departs from i (namely $AG\$AReach[i] = \max(RN\$A[RN\$toAG == i])$).
AG\$W	Adjacency matrix (AG\$nNodes by AG\$nNodes) at the AG level. It is a spam object.
AG\$downNode	Vector (of length AG\$nNodes) representing the adjacency matrix at AG level in a vector form: if $AG\$downNode[i] = j$ then $AG\$W[i, j] = 1$. If o is the outlet node, then $AG\$downNode[o] = 0$.
AG\$leng	Vector (of length AG\$nNodes) of lengths of edges departing from nodes at AG level. Note that AGleng[i] = \sum(RN$leng[RN\$toAG == i])$. If o is an outlet node (i.e. $(o \%in\% AG$outlet) = TRUE$), then AGleng[i] = 0$.
AG\$nNodes	Number of nodes resulting from the aggregation process.
AG\$nUpstream	Vector (of length AG\$nNodes) providing the number of nodes (at the AG level) upstream of each node (the node itself is included).
AG\$outlet	Vector (of length OCN\$FD\$nOutlet) with indices of outlet nodes, i.e. nodes whose $AG\$downNode$ value is 0.
AG\$slope	Vector (of length AG\$nNodes) of slopes at AG level. It represents the (weighted) average slope of edges departing from nodes. If i is an outlet node (i.e. $(i \%in\% AG$outlet) = TRUE$), then AGslope[i] = NaN$.
AG\$streamOrder	Vector (of length AG\$nNodes) of stream order values for each node. If $streamOrderType = "Strahler"$, Strahler stream order is computed. If $streamOrderType = "Shreve"$, Shreve stream order is computed.
AG\$upstream	List (of length AG\$nNodes) whose object i is a vector (of length AG\$nUpstream[i]) containing the indices of nodes (at the AG level) upstream of a node i (including i).
AG\$toFD	Vector (of length AG\$nNodes) with with indices at FD level of nodes belonging to AG level. AGtoFD[i] = j$ implies OCNFD$toAG[j] = i$.
AG\$ReachToFD	List (of length AG\$nNodes) whose object i is a vector of indices of FD nodes constituting the edge departing from node i .
AG\$toRN	Vector (of length AG\$nNodes) with with indices at RN level of nodes belonging to AG level. AGtoRN[i] = j$ implies OCNFD$toRN[j] = i$.
AG\$ReachToRN	List (of length AG\$nNodes) whose object i is a vector of indices of RN nodes constituting the edge departing from node i .
AG\$toCM	Vector (of length AG\$nNodes) with catchment index values for each AG node. Example: AGtoCM[i] = j$ if node i drains into the outlet whose location is defined by $outletSide[j]$, $outletPos[j]$.
AG\$X, AG\$Y	Vectors (of length AG\$nNodes) of X, Y coordinates (in planar units) of nodes at the AG level. These correspond to the X, Y coordinates of the nodes constituting the upstream tips of the reaches. If i and j are such that AGX[i] == RN$X[j]$ and AGY[i] == RN$Y[j]$, then AGA[i] = RN$A[j]$.

AG\$XReach, AG\$YReach	Vector (of length AG\$nNodes) of X, Y coordinates (in planar units) of the downstream tips of the reaches. If i and j are such that $AG\$XReach[i] == RN\$X[j]$ and $AG\$YReach[i] == RN\$Y[j]$, then $AG\$AReach[i] = RN\$A[j]$. If o is an outlet node, then $AG\$XReach = NaN$, $AG\$YReach = NaN$.
AG\$Z	Vector (of length AG\$nNodes) of elevation values (in elevational units) of nodes at the AG level. These correspond to the elevations of the nodes constituting the upstream tips of the reaches.
AG\$ZReach	Vector (of length AG\$nNodes) of Z coordinates (in elevational units) of the downstream tips of the reaches. If o is an outlet node, then $AG\$ZReach = NaN$.
SC\$ALocal	Vector (of length SC\$nNodes) with values of subcatchment area, that is the number of FD pixels (multiplied by $OCN\$FD\$cellsize^2$) that constitutes a subcatchment. If o is an outlet node, then $ALocal[o] = 0$.
SC\$W	Adjacency matrix (SC\$nNodes by SC\$nNodes) at the subcatchment level. Two subcatchments are connected if they share a border. Note that this is not a flow connection. Unlike the adjacency matrices at levels FD, RN, AG, this matrix is symmetric. It is a spam object. If o is an outlet node, then $SC\$W[o,]$ and $SC\$W[, o]$ only contain zeros (i.e., o is unconnected to the other nodes).
SC\$nNodes	Number of subcatchments into which the lattice is partitioned. If $nOutlet = 1$, then SCnNodes = AG$nNodes$. If multiple outlets are present, SCnNodes$ might be greater than AGnNodes$ in the case when some catchments have drainage area lower than $thrA$. In this case, the indices from AGnNodes + 1$ to SCnNodes$ identify subcatchment that do not have a corresponding AG node.
SC\$toFD	List (of length SC\$nNodes) whose object i is a vector of indices of FD pixels constituting the subcatchment i .
SC\$X, SC\$Y	Vectors (of length SC\$nNodes) of X, Y coordinates (in planar units) of subcatchment centroids.
SC\$Z	Vector (of length SC\$nNodes) of average subcatchment elevation (in elevational units).

Finally, $thrA$ is added to the list.

Examples

```
# 1) aggregate a 20x20 OCN by imposing thrA = 4
OCN <- aggregate_OCN(landscape_OCN(OCN_20), thrA = 4)

# 2) explore the effects of thrA and maxReachLength on a large OCN
OCN <- landscape_OCN(OCN_250_T) # it takes some seconds
OCN_a <- aggregate_OCN(OCN, thrA = 200) # it takes some seconds
OCN_b <- aggregate_OCN(OCN, thrA = 1000) # it takes some seconds
OCN_c <- aggregate_OCN(OCN, thrA = 1000, maxReachLength = 20) # it takes some seconds

old.par <- par(no.readonly = TRUE)
par(mfrow = c(1,3))
draw_subcatchments_OCN(OCN_a)
points(OCN_a$AG$X, OCN_a$AG$Y, pch = 19, col = "#0044bb")
```

```

title(paste("No. AG nodes = ", as.character(OCN_a$AG$nNodes),
sep=""))
draw_subcatchments_OCN(OCN_b)
points(OCN_b$AG$X, OCN_b$AG$Y, pch = 19, col = "#0044bb")
title(paste("No. AG nodes = ", as.character(OCN_b$AG$nNodes),
sep=""))
draw_subcatchments_OCN(OCN_c)
points(OCN_c$AG$X, OCN_c$AG$Y, pch = 19, col = "#0044bb")
title(paste("No. AG nodes = ", as.character(OCN_c$AG$nNodes),
sep=""))
par(old.par)

```

create_OCN

Create an Optimal Channel Network

Description

Function that performs the OCN search algorithm on a rectangular lattice and creates OCN at the flow direction (FD) level.

Usage

```

create_OCN(dimX, dimY, nOutlet = 1, outletSide = "S",
outletPos = round(dimX/3), periodicBoundaries = FALSE,
typeInitialState = NULL, flowDirStart = NULL, expEnergy = 0.5,
cellsize = 1, xllcorner = 0.5 * cellsize, yllcorner = 0.5 *
cellsize, nIter = 40 * dimX * dimY, nUpdates = 50,
initialNoCoolingPhase = 0, coolingRate = 1,
showIntermediatePlots = FALSE, thrADraw = 0.002 * dimX * dimY *
cellsize^2, easyDraw = NULL, saveEnergy = FALSE, saveExitFlag = FALSE,
saveN8 = FALSE, saveN4 = FALSE, displayUpdates = 1)

```

Arguments

dimX	Longitudinal dimension of the lattice (in number of pixels).
dimY	Latitudinal dimension of the lattice (in number of pixels).
nOutlet	Number of outlets. If nOutlet = "All", all border pixels are set as outlets.
outletSide	Side of the lattice where the outlet(s) is/are placed. It is a vector of characters, whose allowed values are "N" (northern side), "E", "S", "W". Its length must be equal to nOutlet.
outletPos	Vector of positions of outlets within the sides specified by outletSide. If outletSide[i] = "N" or "S", then outletPos[i] must be a natural number in the interval 1:dimX; if outletSide[i] = "W" or "E", then outletPos[i] must be a natural number in the interval 1:dimY. If nOutlet > 1 is specified by the user and outletSide, outletPos are not, a number of outlets equal to nOutlet is randomly drawn among the border pixels. Its length must be equal to nOutlet.

periodicBoundaries	If TRUE, periodic boundaries are applied. In this case, the lattice is the planar equivalent of a torus.
typeInitialState	Configuration of the initial state of the network. Possible values: "I" (representing a valley); "T" (T-shaped drainage pattern); "V" (V-shaped drainage pattern); "H" (hip roof). Default value is set to "I", unless when nOutlet = "All", where default is "H". See Details for explanation on initial network state in the multiple outlet case.
flowDirStart	Matrix (dimY by dimX) with custom initial flow directions. Possible entries to flowDirStart are natural numbers between 1 and 8. Key is as follows (capital letters indicate cardinal directions) <ul style="list-style-type: none"> 1 E (+1 column) 2 SE (-1 row, +1 column) 3 S (-1 row) 4 SW (-1 row, -1 column) 5 W (-1 column) 6 NW (+1 row, -1 column) 7 N (+1 row) 8 NE (+1 row, +1 column)
expEnergy	Exponent of the functional $\sum(A^{\text{expEnergy}})$ that is minimized during the OCN search algorithm.
cellsize	Size of a pixel in planar units.
xllcorner	Longitudinal coordinate of the lower-left pixel.
yllcorner	Latitudinal coordinate of the lower-left pixel.
nIter	Number of iterations for the OCN search algorithm.
nUpdates	Number of updates given during the OCN search process (only effective if any(displayUpdates, showIntermediatePlots)=TRUE.).
initialNoCoolingPhase, coolingRate	Parameters of the function used to describe the temperature of the simulated annealing algorithm. See details.
showIntermediatePlots	If TRUE, the OCN plot is updated nUpdates times during the OCN search process. Note that, for large lattices, showIntermediatePlots = TRUE might slow down the search process considerably (especially when easyDraw = FALSE).
thrADraw	Threshold drainage area value used to display the network (only effective when showIntermediatePlots = TRUE).
easyDraw	Logical. If TRUE, the whole network is displayed (when showIntermediatePlots = TRUE), and pixels with drainage area lower than thrADraw are displayed in light gray. If FALSE, only pixels with drainage area greater or equal to thrADraw are displayed. Default is FALSE if dimX*dimY <= 40000, and TRUE otherwise. Note that setting easyDraw = FALSE for large networks might slow down the process considerably.
saveEnergy	If TRUE, energy is saved (see Value for its definition).

saveExitFlag	If TRUE, exitFlag is saved (see Value for its definition).
saveN8	If TRUE, the adjacency matrix relative to 8-nearest-neighbours connectivity is saved.
saveN4	If TRUE, the adjacency matrix relative to 4-nearest-neighbours connectivity is saved.
displayUpdates	State if updates are printed on the console while the OCN search algorithm runs. <ul style="list-style-type: none"> 0 No update is given. 1 An estimate of duration is given (only if $\text{dimX} \times \text{dimY} > 1000$, otherwise no update is given). 2 Progress updates are given. The number of these is controlled by nUpdates

Details

Simulated annealing temperature. The function that expresses the temperature of the simulated annealing process is as follows:

```

if i <= initialNoCoolingPhase*nIter: Temperature[i] = Energy[1]
if initialNoCoolingPhase*nIter < i <= nIter: Temperature[i] = Energy[1]*(-coolingRate*(i
-InitialNoCoolingPhase*nIter)/nNodes)

```

where i is the index of the current iteration and $\text{Energy}[1] = \sum(A^{\text{expEnergy}})$, with A denoting the vector of drainage areas corresponding to the initial state of the network. According to the simulated annealing principle, a new network configuration obtained at iteration i is accepted with probability equal to $\exp((\text{Energy}[i] - \text{Energy}[i-1]) / \text{Temperature}[i])$ if $\text{Energy}[i] < \text{Energy}[i-1]$. To ensure convergence, it is recommended to use coolingRate values between 0.5 and 10 and initialNoCoolingPhase ≤ 0.3 . Low coolingRate and high initialNoCoolingPhase values cause the network configuration to depart more significantly from the initial state. If coolingRate < 0.5 and initialNoCoolingPhase > 0.1 are used, it is suggested to increase nIter with respect to the default value in order to guarantee convergence.

Initial network state. If nOutlet > 1 , the initial state is applied with regards to the outlet located at outletSide[1], outletPos[1]. Subsequently, for each of the other outlets, the drainage pattern is altered within a region of maximum size $0.5 \times \text{dimX}$ by $0.25 \times \text{dimY}$ for outlets located at the eastern and western borders of the lattice, and $0.25 \times \text{dimX}$ by $0.5 \times \text{dimY}$ for outlets located at the southern and northern borders of the lattice. The midpoint of the long size of the regions coincides with the outlet at stake. Within these regions, an "I"-type drainage pattern is produced if typeInitialState = "I" or "T"; a "V"-type drainage pattern is produced if typeInitialState = "V"; no action is performed if typeInitialState = "H". Note that typeInitialState = "H" is the recommended choice only for large nOutlet.

Suggestions for creating "fancy" OCNs. In order to generate networks spanning a realistic, non-rectangular catchment domain (in the "real-shape" view provided by draw_contour_OCN), it is convenient to use the option periodicBoundaries = TRUE and impose at least a couple of diagonally adjacent outlets on two opposite sides, for example nOutlet = 2, outletSide = c("S", "N"), outletPos = c(1, 2). See also OCN_300_4out_PB_hot. Note that, because the OCN search algorithm is a stochastic process, the successful generation of a "fancy" OCN is not guaranteed: indeed, it is possible that the final outcome is a network where most (if not all) pixels drain towards one of the two outlets, and hence such outlet is surrounded (in the "real-shape" view) by the pixels that it

drains. Note that, in order to hinder such occurrence, the two pixels along the lattice perimeter next to each outlet are bound to drain towards such outlet.

In order to create a network spanning a "pear-shaped" catchment (namely where the width of the area spanned in the direction orthogonal to the main stem diminishes downstream, until it coincides with the river width at the outlet), it is convenient to use the option `nOutlet = "All"` (here the value of `periodicBoundaries` is irrelevant) and then pick a single catchment (presumably one with rather large catchment area, see value `OCNCMA` generated by `landscape_OCN`) among the many generated. Note that it is not possible to predict the area spanned by such catchment *a priori*. To obtain a catchment whose size is rather large compared to the size of the lattice where the OCN was generated, it is convenient to set `typeInitialState = "I"` and then pick the catchment with largest area (`landscape_OCN` must be run).

The default temperature schedule for the simulated annealing process is generally adequate for generating an OCN that does not resemble the initial network state if the size of the lattice is not too large (say, until $\text{dimX} \times \text{dimY} \leq 40000$). When $\text{dimX} \times \text{dimY} > 40000$, it might be convenient to make use of a "warmer" temperature schedule (for example, by setting `coolingRate = 0.5` and `initialNoCoolingPhase = 0.1`; see also the package vignette) and/or increase `nIter` with respect to its default value. Note that these suggestions only pertain to the aesthetics of the final OCN; the default temperature schedule and `nIter` are calibrated to ensure convergence of the OCN (i.e. achievement of a local minimum of Energy, save for a reasonable threshold) also for lattices larger than $\text{dimX} \times \text{dimY} = 40000$.

Value

A list whose objects are listed below. Variables that define the network at the FD level are wrapped in the sublist `FD`. Adjacency matrices describing 4- or 8- nearest-neighbours connectivity among pixels are contained in lists `N4` and `N8`, respectively.

<code>FD\$A</code>	Vector (of length $\text{dimX} \times \text{dimY}$) containing drainage area values for all FD pixels (in square planar units).
<code>FD\$W</code>	Adjacency matrix ($\text{dimX} \times \text{dimY}$ by $\text{dimX} \times \text{dimY}$) at the FD level. It is a <code>spam</code> object.
<code>FD\$downNode</code>	Vector (of length $\text{dimX} \times \text{dimY}$) representing the adjacency matrix at FD level in a vector form: if <code>FD\$downNode[i] = j</code> then <code>FD\$W[i, j] = 1</code> . If <code>o</code> is the outlet pixel, then <code>FD\$downNode[o] = 0</code> .
<code>FD\$X (FD\$Y)</code>	Vector (of length $\text{dimX} \times \text{dimY}$) containing X (Y) coordinate values for all FD pixels.
<code>FD\$nNodes</code>	Number of nodes at FD level (equal to $\text{dimX} \times \text{dimY}$).
<code>FD\$outlet</code>	Vector (of length <code>nOutlet</code>) indices of pixels at FD level corresponding to outlets.
<code>energy</code>	Vector (of length <code>nIter</code>) of energy values for each stage of the OCN during the search algorithm (only present if <code>saveEnergy = TRUE</code>).
<code>exitFlag</code>	Vector (of length <code>nIter</code>) showing the outcome of the rewiring process (only present if <code>saveExitFlag = TRUE</code>). Its entries can assume one of the following values: <ul style="list-style-type: none"> <code>0</code> Rewiring is accepted. <code>1</code> Rewiring is not accepted (because it does not lower Energy or according to the acceptance probability of the simulated annealing algorithm).

- 2 Rewiring is invalid because a loop in the graph was generated, therefore the network is no longer a direct acyclic graph.
- 3 Rewiring is invalid because of cross-flow. This means that, for example, in a 2x2 cluster of pixel, the southwestern (SW) corner drains into the NE one, and SE drains into NW. Although this circumstance does not imply the presence of a loop in the graph, it has no physical meaning and is thereby forbidden.

N4\$W Adjacency matrix (dimX*dimY by dimX*dimY) that describes 4-nearest-neighbours connectivity between pixels: $N4\$W[i, j] = 1$ if pixel j shares an edge with i , and is null otherwise. It is saved only if `saveN4 = TRUE`.

N8\$W Adjacency matrix (dimX*dimY by dimX*dimY) that describes 8-nearest-neighbours connectivity between pixels: $N8\$W[i, j] = 1$ if pixel j shares an edge or a vertex with i , and is null otherwise. It is saved only if `saveN8 = TRUE`.

Finally, `dimX`, `dimY`, `cellsize`, `nOutlet`, `periodicBoundaries`, `expEnergy`, `coolingRate`, `typeInitialState`, `nIter` are passed to the list as they were included in the input (except `nOutlet = "All"` which is converted to $2*(dimX + dimY - 2)$).

Examples

```
# 1) creates and displays a single outlet 20x20 OCN with default options
set.seed(1)
OCN_a <- create_OCN(20, 20)
draw_simple_OCN(OCN_a)

# 2) creates and displays a 2-outlet OCNs with manually set outlet location,
# and a 4-outlet OCNs with random outlet position.
set.seed(1)
old.par <- par(no.readonly = TRUE)
par(mfrow=c(1,2))
OCN_b1 <- create_OCN(30, 30, nOutlet = 2, outletSide = c("N", "W"), outletPos = c(15, 12))
OCN_b2 <- create_OCN(30, 30, nOutlet = 4)
draw_simple_OCN(OCN_b1)
title("2-outlet OCN")
draw_simple_OCN(OCN_b2)
title("4-outlet OCN")
par(old.par)

# 3) generate 3 single-outlet OCNs on the same (100x100) domain starting from different
# initial states, and show 20 intermediate plots and console updates.
set.seed(1)
OCN_V <- create_OCN(100, 100, typeInitialState = "V", showIntermediatePlots = TRUE,
nUpdates = 20, displayUpdates = 2)
OCN_T <- create_OCN(100, 100, typeInitialState = "T", showIntermediatePlots = TRUE,
nUpdates = 20, displayUpdates = 2)
OCN_I <- create_OCN(100, 100, typeInitialState = "I", showIntermediatePlots = TRUE,
nUpdates = 20, displayUpdates = 2)
```

```
# 4) generate a 2-outlet OCN and show intermediate plots. Note that different colors are used
# to identify the two networks (all pixels are colored because thrADraw = 0).
set.seed(1)
OCN <- create_OCN(150, 70, nOutlet = 2, outletPos = c(1, 150), outletSide = c("S", "N"),
typeInitialState = "V", periodicBoundaries = TRUE,
showIntermediatePlots = TRUE, thrADraw = 0)
# The resulting networks have an irregular contour, and their outlets are located on the contour:
draw_contour_OCN(landscape_OCN(OCN))
```

create_peano

Create Peano network

Description

Function that creates Peano networks on a square lattice.

Usage

```
create_peano(nIterPeano, outletPos = "NE", xllcorner = 1,
  yllcorner = 1, cellsize = 1)
```

Arguments

nIterPeano	Number of iteration of the Peano scheme. The resulting network will span a domain of size $2^{(nIterPeano + 1)}$ by $2^{(nIterPeano + 1)}$.
outletPos	Corner where the outlet is located, expressed as intercardinal direction. Possible values are "NE", "SE", "SW", "NW".
xllcorner	X coordinate of the lower-left pixel (expressed in planar units).
yllcorner	Y coordinate of the lower-left pixel (expressed in planar units).
cellsize	Size of a pixel (expressed in planar units).

Value

A list that contains the same objects as those produced by [create_OCN](#). As such, it can be used as input for all other complementary functions of the package.

Examples

```
# 1) create a peano network in a 32x32 square,
# use landscape_OCN, aggregate_OCN functions,
# and display subcatchment map and map of drainage area
peano <- create_peano(4)
peano <- aggregate_OCN(landscape_OCN(peano), thrA = 4)
old.par <- par(no.readonly = TRUE)
par(mfrow=c(1,3))
```

```

draw_simple_OCN(peano)
title("Peano network")
draw_subcatchments_OCN(peano)
title("Subcatchments")
draw_thematic_OCN(peano$RN$A, peano)
title("Drainage area at RN level")
par(old.par)

```

draw_contour_OCN *Draw Optimal Channel Network with catchment contours*

Description

Function that plots real-shaped OCN and catchment contours.

Usage

```

draw_contour_OCN(OCN, thrADraw = 0.002 * OCN$dimX * OCN$dimY *
  OCN$cellsize^2, exactDraw = TRUE, drawContours = TRUE, colPalRiver = NULL,
  colPalCont = "#000000", drawOutlets = 0, pch = 15, colPalOut = "#000000")

```

Arguments

OCN	List as produced by landscape_OCN .
thrADraw	Threshold drainage area value used to display the network.
exactDraw	If TRUE, the real shape of OCNs is plotted. If flow crosses a boundary, the pixel that is not contiguous to its outlet is flipped. It is only effective if <code>OCN\$PeriodicBoundaries = TRUE</code>
drawContours	If TRUE, plot catchment(s) contours.
colPalRiver	Color palette used to plot the river network(s). Default is a rearranged version of theme "Dark 3" (see hcl.pals). <code>colPalRiver</code> accepts both functions creating color palettes and vectors of colors (of which the first <code>OCN\$nOutlet</code> elements are used). If a single color value is provided and <code>OCN\$nOutlet > 1</code> , all river networks are drawn with the same color.
colPalCont	Color palette used to plot the catchment contour(s). Details as in <code>colPalRiver</code> . Additionally, if <code>colPalCont = 0</code> , the palette specified in <code>colPalRiver</code> is copied.
drawOutlets	If equal to 1, black squares are drawn at the outlets' locations behind the river; if 2 they are plotted on top of the river.
pch	Shape of the outlet points (if <code>drawOutlets = TRUE</code>). See points for legend.
colPalOut	Color palette used to plot the outlet points (if <code>drawOutlets = TRUE</code>). Details as in <code>colPalRiver</code> . Additionally, if <code>colPalOut = 0</code> , the palette specified in <code>colPalRiver</code> is copied.

Details

For not too large networks (i.e. if $OCN\$FD\$nNodes \leq 40000$, corresponding to a 200x200 lattice), pixels whose drainage area $OCN\$FD\A is lower than $thrADraw$ are drawn with a light grey stroke. If $OCN\$FD\$nNodes > 40000$, in order to speed up the execution of this function, only the network constituted by pixels such that $OCN\$FD\$A > thrADraw$ is drawn.

Value

No output is returned.

Examples

```
# 1) draw contour of a 20x20 single-outlet OCN
# (for single-outlet OCNs without periodic boundaries, the output
# of draw_contour_OCN is very similar to that of draw_simple_OCN)
draw_contour_OCN(landscape_OCN(OCN_20), thrADraw = 4)

# 2a) plot real shape of multiple-outlet OCN created with periodic boundaries
# add outlets on top of the rivers
OCN <- landscape_OCN(OCN_30_4out_PB) # it takes around one minute
draw_contour_OCN(OCN, drawOutlets = 2)

# 2b) same as before, but use same color palette for rivers and contours
draw_contour_OCN(OCN, colPalCont = 0)

# 2c) draw contours of catchments obtained from an OCN with nOutlet = "All"
OCN <- landscape_OCN(OCN_400_Allout) # it takes some minutes
draw_contour_OCN(OCN)

# 2d) same as above, but do not plot contours, and plot outlets
# with same color palette as rivers
draw_contour_OCN(OCN, drawContours = FALSE, drawOutlets = TRUE,
colPalOut = 0)
```

draw_elev2D_OCN

Plot 2D map of elevation generated by an OCN

Description

Function that plots the 2D elevation map generated by an OCN.

Usage

```
draw_elev2D_OCN(OCN, colPalette = terrain.colors(1000, alpha = 1))
```

Arguments

OCN	List as produced by landscape_OCN .
colPalette	Color palette used for the plot.

Value

No output is returned.

Examples

```
# 1) draw 2D map of a 20x20 OCN with default settings
draw_elev2D_OCN(landscape_OCN(OCN_20))
```

draw_elev3Drgl_OCN	<i>Plot 3D map of elevation generated by an OCN via rgl rendering</i>
--------------------	---

Description

Function that plots the 3D elevation map generated by an OCN.

Usage

```
draw_elev3Drgl_OCN(OCN, coarseGrain = c(1, 1), chooseCM = FALSE,
  addColorbar = FALSE, drawRiver = FALSE, thrADraw = 0.002 *
  OCN$dimX * OCN$dimY * OCN$cellsize^2, riverColor = "#00CCFF", ...)
```

Arguments

OCN	List as produced by landscape_OCN .
coarseGrain	2x1 vector (only effective if chooseCM = FALSE). For aesthetic purposes, the elevation map can be coarse-grained into a $OCN\$dimX/coarseGrain[1]$ -by- $OCN\$dimY/coarseGrain[2]$ domain, where each cell's elevation is the average of elevations of the corresponding $coarseGrain[1]$ -by- $coarseGrain[2]$ cells of the original elevation field. $coarseGrain[1]$ and $coarseGrain[2]$ must be divisors of $OCN\$dimX$ and $OCN\$dimY$, respectively. $coarseGrain = c(2, 2)$ is often sufficient to achieve a good graphical results for large (i.e. at least 100x100 nodes) OCNs.
chooseCM	Index of catchment to display (only effective if $OCN\$nOutlet > 1$). It can be a logical, or a scalar within $1:length(OCN\$nOutlet)$. If TRUE, the catchment with largest area is displayed. Note that, if the size of the chosen catchment is too small (e.g. $OCN\$CM\$A[chooseCM] < 5*OCN\$cellsize^2$), an error might occur due to failure in triangulation.
addColorbar	If TRUE, add colorbar to the plot.
drawRiver	If TRUE, draw the OCN on top of the elevation field.
thrADraw	Threshold drainage area value used to display the network.

riverColor Color used to plot the river.

... Further parameters passed to function `persp3d`. The default value for aspect is `c(OCN$dimX/sqrt(OCN$dimX*OCN$dimY),OCN$dimY/sqrt(OCN$dimX*OCN$dimY),1)`.

Details

This function makes use of the `rgl` rendering system. To export the figure in raster format, use `rgl.snapshot`. To export in vectorial format, use `rgl.postscript` (but note that this might produce rendering issues, see `rgl` for details). The function will attempt at drawing a contour of the plotted entity (i.e. the lattice or a catchment, depending on `chooseCM`) at null elevation, and drawing polygons connecting this contour with the lattice/catchment contour at the real elevation. If `chooseCM != FALSE`, this might result in errors owing to failure of `polygon3d` in triangulating the polygons.

Value

No output is returned.

Examples

```
draw_elev3Drgl_OCN(landscape_OCN(OCN_20))

# 1a) draw the 3D representation of a single catchment within an OCN
# generated with nOutlet = "All" and add draw the river on top of it
OCN <- landscape_OCN(OCN_400_Allout) # this takes some minutes
draw_elev3Drgl_OCN(OCN, chooseCM = 983, drawRiver = TRUE)

# 1b) draw the 3D representation of the largest catchment within the OCN
# (here polygon3d may fail at plotting the polygon at zero elevation)
draw_elev3Drgl_OCN(OCN, chooseCM = TRUE)

# 1c) draw the 3D representation of the whole OCN
# and enhance the aspect ratio of Z coordinates
# with respect to the default value (the final result will be ugly):
draw_elev3Drgl_OCN(OCN, aspect = c(1, 1, 0.2))

# 1d) same as above, but operate coarse graining for better aesthetics:
draw_elev3Drgl_OCN(OCN, coarseGrain = c(5,5), aspect = c(1, 1, 0.2))

# 2) draw the 3D representation of a single catchment of an OCN generated
# with periodicBoundaries = TRUE
# (note that the real shape of the catchment is drawn)
OCN <- landscape_OCN(OCN_300_4out_PB) # this takes some minutes
draw_elev3Drgl_OCN(OCN, chooseCM = TRUE)
```

draw_elev3D_OCN *Plot 3D map of elevation generated by an OCN*

Description

Function that plots the 3D elevation map generated by an OCN.

Usage

```
draw_elev3D_OCN(OCN, coarseGrain = c(1,1), colPalette = terrain.colors(1000, alpha = 1),
  addColorbar = TRUE, drawRiver = TRUE, thrADraw = 0.002 *
  OCN$dimX * OCN$dimY * OCN$cellsize^2, riverColor = "#00CCFF",
  theta = -20, phi = 30, expand = 0.05, shade = 0.5)
```

Arguments

OCN	List as produced by landscape_OCN .
coarseGrain	2x1 vector (only effective if chooseCM = FALSE). For aesthetic purposes, the elevation map can be coarse-grained into a OCN\$dimX/coarseGrain[1]-by-OCN\$dimY/coarseGrain[2] domain, where each cell's elevation is the average of elevations of the corresponding coarseGrain[1]-by-coarseGrain[2] cells of the original elevation field. coarseGrain[1] and coarseGrain[2] must be divisors of OCN\$dimX and OCN\$dimY, respectively. coarseGrain = c(2,2) is often sufficient to achieve a good graphical results for large (i.e. at least 100x100 nodes) OCNs.
colPalette	Color palette used for the plot.
addColorbar	If TRUE, add colorbar to the plot.
drawRiver	If TRUE, draw the OCN on top of the elevation field.
thrADraw	Threshold drainage area value used to display the network.
riverColor	Color used to plot the river.
theta, phi, expand, shade	Additional parameters passed to the perspective plotting function persp . theta expresses azimuthal direction; phi gives colatitude; expand is the expansion factor for the Z coordinates; shade controls the shade at a surface facet.

Value

No output is returned.

Examples

```
# draw 3D representation of a 20x20 OCN with default options
draw_elev3D_OCN(landscape_OCN(OCN_20))
```

```
# 1a) draw the 3D representation of the OCN (without displaying the river
```

```
# and the colorbar) and enhance the aspect ratio of Z coordinates
# with respect to the default value (the final result will be ugly):
OCN <- landscape_OCN(OCN_400_Allout) # this takes some minutes
draw_elev3D_OCN(OCN, expand = 0.2, addColorbar = FALSE, drawRiver = FALSE)

# 1b) same as above, but operate coarse graining and modify shade for better aesthetics:
draw_elev3D_OCN(OCN, coarseGrain = c(5,5), expand = 0.2,
shade = 0.25, addColorbar = FALSE, drawRiver = FALSE)
```

draw_simple_OCN

Draw an Optimal Channel Network

Description

Function that plots the non-aggregated OCN as calculated by `create_OCN`.

Usage

```
draw_simple_OCN(OCN, thrADraw = 0.002 * OCN$dimX * OCN$dimY *
  OCN$cellsize^2, riverColor = "#0066FF", easyDraw = NULL)
```

Arguments

OCN	List as produced by create_OCN .
thrADraw	Threshold drainage area value used to display the network.
riverColor	Color used to plot the river.
easyDraw	Logical. If TRUE, the whole network is displayed, and pixels with drainage area lower than thrADraw are displayed in light gray. If FALSE, only pixels with drainage area greater or equal to thrADraw are displayed. Default is FALSE if <code>OCN\$nNodes <= 40000</code> , and TRUE otherwise. Note that setting <code>easyDraw = FALSE</code> for large networks might slow down the process considerably.

Value

No output is returned.

Examples

```
# 1a) draw OCN with default settings
draw_simple_OCN(OCN_250_T)
# 1b) same as above, but with decreased thrADraw
draw_simple_OCN(OCN_250_T, thrADraw = 0.001 * OCN_250_T$dimX * OCN_250_T$dimY)

# 1c) same as the first example, but include the portion of network
# with drainage area lower than thrADraw
draw_simple_OCN(OCN_250_T, easyDraw = FALSE) # this will take some seconds
```

`draw_subcatchments_OCN`*Draw subcatchment map from an Optimal Channel Network*

Description

Function that draws a map of subcatchments generated by the aggregation process on the OCN.

Usage

```
draw_subcatchments_OCN(OCN, drawRiver = TRUE, colPalette = NULL)
```

Arguments

<code>OCN</code>	List as produced by aggregate_OCN .
<code>drawRiver</code>	if TRUE, draw the OCN on top of the subcatchment map.
<code>colPalette</code>	Color palette used. Default is <code>c("#009900", "#FFFF00", "#FF9900", "#FF0000", "#FF00FF", "#9900CC")</code> . Only the first <code>n</code> colors are used, where <code>n</code> is the number of different colors needed (calculated via a greedy coloring algorithm). <code>colPalette</code> accepts both functions creating color palettes and vectors of colors (see examples); in the latter case, the length of the vector cannot be lower than <code>n</code> (<code>n</code> cannot be predicted a priori, but generally 6 colors should suffice).

Value

No output is returned.

Examples

```
# 1a) aggregate a 20x20 OCN , use thrA = 5 pixels
# and draw subcatchments with default color palette
OCN <- aggregate_OCN(landscape_OCN(OCN_20), thrA = 5)
draw_subcatchments_OCN(OCN, drawRiver = TRUE)

# 1b) same as above, but define color palette with a function
draw_subcatchments_OCN(OCN, drawRiver = TRUE, colPalette = rainbow)

# 1c) same as above, but define color palette with a vector of colors
draw_subcatchments_OCN(OCN, drawRiver = TRUE, colPalette = hcl.colors(6, "Dark 3"))
```

draw_thematic_OCN *Draw thematic map on an Optimal Channel Network*

Description

Function that draws OCNs with color of RN or AG nodes depending on an arbitrary theme.

Usage

```
draw_thematic_OCN(theme, OCN,
  chooseAggregation = NULL,
  discreteLevels = FALSE,
  colLevels = NULL, cutoff = FALSE,
  colPalette = colorRampPalette(c("yellow", "red", "black")),
  exactDraw = FALSE, chooseCM = FALSE, drawNodes = FALSE,
  cex = 2, pch = 21, nanColor = "#0099FF",
  riverColor = "#0099FF", backgroundColor = "#999999",
  addLegend = TRUE)
```

Arguments

theme	Vector (of length OCN\$AG\$Nnodes or OCN\$RN\$Nnodes) expressing the spatial field of interest. The vector can contain NA and NaN values to identify RN or AG nodes where the theme is not defined.
OCN	List as produced by aggregate_OCN .
chooseAggregation	Only effective if OCN\$RN\$Nnodes == OCN\$AG\$Nnodes. In such case, it must be equal to either "RN" or "AG"; as a result, theme will be interpreted as a spatial field in the corresponding aggregation level.
discreteLevels	Logical. If FALSE, a continuous color scheme is used. If TRUE, discrete color levels are applied. See also colLevels and examples.
colLevels	Number of colors in the palette. If discreteLevels == FALSE, colLevels must be a vector of the form c(minval,maxval,N_levels). The vector of breakpoints used to attribute theme values to a given color is then defined as seq(minval,maxval,N_levels). Default is minval = min(theme[!(is.nan(theme))]), maxval = max(theme[!(is.nan(theme))]), N_levels = 1000. If discreteLevels == TRUE and is.null(colLevels) == TRUE, each unique value of theme is attributed a different color. If discreteLevels == TRUE and colLevels is a vector, colLevels is used as vector of breakpoints. In this case, the number of discrete colors is equal to length(colLevels) - 1.
cutoff	Logical. If FALSE, nodes whose theme value is beyond the range established by the vector of breakpoints are attributed the color corresponding to the lowest (or highest) value in the color scheme. If TRUE, such nodes are attributed the color NaNcolor.

colPalette	Color palette used to display theme values. colPalette accepts both functions creating color palettes and vectors of colors. In the latter case, length(colPalette) must be greater than the number of color levels. See examples below and hcl.colors .
chooseCM	Index of catchment to display (only effective if OCN\$N_outlet > 1). It can be a logical or a numeric vector. If FALSE, all catchments are displayed. If TRUE, the catchment with largest area is displayed. If chooseCM is a subset of vector 1:length(OCN\$N_outlet), only the catchment(s) identified by the indices in chooseCM are displayed.
exactDraw	If TRUE, the real shape of OCNs is plotted. If flow crosses a boundary, the pixel that is not contiguous to its outlet is flipped.
drawNodes	If FALSE, the theme is directly displayed on the river network. In this case, the edge departing from a given node is displayed with the color attributed to the node. If TRUE, the theme is displayed via markers at the locations of the nodes at the RN or AG level (depending on the length of theme). In this case, nanColor can be used to define the color of the river network.
cex	Only effective if drawNodes == TRUE. It sets the dimension of the markers (equivalent to parameter cex of function points). It can be a scalar or a vector of length length(theme).
pch	Only effective if drawNodes == TRUE. It sets the type of the markers (equivalent to parameter pch of function points). It can be a scalar or a vector of length length(theme).
nanColor	Color attributed to RN or AG nodes whose theme value is NA or NaN.
riverColor	Only effective if drawNodes == TRUE. Color used to display the OCN below the nodes.
backgroundColor	Color used in the background of the figure. It can be either a single value, or a vector with number of components equal to length(chooseCM). If length(backgroundColor) == length(chooseCM), each color is used to identify a different catchment selected in chooseCM (corresponding to the respective outlet). If instead length(chooseCM) > 1 and length(backgroundColor) == 1, all catchments are colored with the same backgroundColor.
addLegend	If TRUE, add legend to the plot. If discreteLevels = FALSE, this appears a colorbar.

Details

This function can be used to show how a certain spatial field varies along the river network.

Value

No output is returned.

Examples

```
# 1a) Six different ways to display contributing area at the AG level
OCN <- aggregate_OCN(landscape_OCN(OCN_20), thrA = 4)
```

```

old.par <- par(no.readonly = TRUE)
par(mfrow=c(2,3), oma = c(0, 0, 3, 0))
draw_thematic_OCN(OCN$AG$A, OCN, colPalette = hcl.colors)
title("Continuous levels \n Colors on edges")
draw_thematic_OCN(OCN$AG$A, OCN, discreteLevels = TRUE,
colPalette = hcl.colors)
title("Discrete, unique levels \n Colors on edges")
draw_thematic_OCN(OCN$AG$A, OCN, discreteLevels = TRUE,
colLevels = c(1, 10, 50, 100, 500),
colPalette = hcl.colors)
title("Discrete, user-defined levels \n Colors on edges")
draw_thematic_OCN(OCN$AG$A, OCN, drawNodes = TRUE,
colPalette = hcl.colors)
title("Continuous levels \n Colors on edges")
draw_thematic_OCN(OCN$AG$A, OCN, discreteLevels = TRUE,
drawNodes = TRUE, colPalette = hcl.colors)
title("Discrete, unique levels \n Colors on nodes")
draw_thematic_OCN(OCN$AG$A, OCN, discreteLevels = TRUE,
drawNodes = TRUE, colLevels = c(1, 10, 50, 100, 500),
colPalette = hcl.colors)
title("Discrete, user-defined levels \n Colors on nodes")
mtext("Six different ways to display contributing area [no. pixels]", outer = TRUE, cex = 1.5)
par(old.par)

# 1b) Same as above, but use different colLevels, cutoff combinations
# with DiscreteLevels = FALSE
old.par <- par(no.readonly = TRUE)
par(mfrow=c(1,2))
draw_thematic_OCN(OCN$AG$A, OCN, drawNodes = TRUE,
colLevels = c(0, 200, 1000), colPalette = hcl.colors)
title("All nodes with A > 200 pixels \n are displayed in yellow")
draw_thematic_OCN(OCN$AG$A, OCN, drawNodes = TRUE,
nanColor = "#00000000", colLevels = c(0, 200, 1000),
cutoff = TRUE, colPalette = hcl.colors)
title("All nodes with A > 200 pixels \n are treated as NaN")
par(old.par)

# 2) Display distance to outlet (at the RN level) along the main stem
# of an OCN
OCN <- aggregate_OCN(landscape_OCN(OCN_250_T)) # this takes some seconds
OCN <- paths_OCN(OCN, pathsRN = TRUE) # this takes some seconds

distanceToOutlet <- OCN$RN$downstreamPathLength[,OCN$RN$outlet]
farthestNode <- which(distanceToOutlet == max(distanceToOutlet))
mainStem <- OCN$RN$downstreamPath[[farthestNode]][[OCN$RN$outlet]]
theme <- rep(NA, OCN$RN$nNodes)
theme[mainStem] <- distanceToOutlet[mainStem]

draw_thematic_OCN(theme, OCN)
title("Distance to outlet along the main stem [pixel units]")

```

 find_area_threshold_OCN

Find relationship between number of nodes and threshold area in an OCN

Description

Function that calculates relationship between threshold area and number of nodes at RN and AG level for a given OCN. It can be used prior to application of [aggregate_OCN](#) in order to derive the drainage area threshold that corresponds to the desired number of nodes of the aggregated network. It is intended for use with single outlet OCNs, although its use with multiple outlet OCNs is allowed (provided that $\max(\text{thrValues}) \leq \min(\text{OCN}\$CM\$A)$).

Usage

```
find_area_threshold_OCN(OCN, thrValues = seq(OCN$cellsize^2,
  min(OCN$CM$A), OCN$cellsize^2), maxReachLength = Inf,
  streamOrderType = "Strahler", displayUpdates = 0)
```

Arguments

OCN	List as produced by landscape_OCN
thrValues	Vector of values of threshold drainage area (in squared planar units) for which the respective number of nodes at the RN and AG levels are computed. Note that it must be $\max(\text{thrValues}) \leq \min(\text{OCN}\$CM\$A)$, otherwise the catchment(s) with area lower than $\max(\text{thrValues})$ degenerate to a network with zero nodes at the RN/AG level.
maxReachLength	Maximum reach length allowed (in planar units). If the path length between a channel head and the downstream confluence is higher than maxReachLength, the reach starting from the channel head will have a length up to maxReachLength, while the next downstream pixel is considered as a new channel head, from which a new reach departs.
streamOrderType	If "Strahler", Strahler stream order is computed; if "Shreve", Shreve stream order is computed.
displayUpdates	If 1, progress updates are printed in the console while the function is running. If 0, no updates are printed.

Value

A list whose objects are listed below.

thrValues	Copy of the input vector with the same name.
nNodesRN	Vector (of the same length as thrValues) of number of nodes at the RN level resulting from the aggregation process with a threshold area values specified by thrValues.

nNodesAG	Vector (of the same length as thrValues) of number of nodes at the AG level resulting from the aggregation process with a threshold area values specified by thrValues.
drainageDensity	Vector (of the same length as thrValues) of values of drainage density of the river network resulting from the aggregation process with a threshold area values specified by thrValues. Drainage density is calculated as total length of the river network divided by area of the lattice. It is expressed in planar units ⁽⁻¹⁾ .
streamOrder	Vector (of the same length as thrValues) of values of maximum stream order attained by the river network, resulting from the aggregation process with a threshold area values specified by thrValues.

Examples

```
# 1) derive relationship between threshold area and number of nodes
OCN <- landscape_OCN(OCN_20)
thr <- find_area_threshold_OCN(OCN)
# log-log plot of number of nodes at the AG level versus
# relative threshold area (as fraction of total drainage area)
old.par <- par(no.readonly = TRUE)
par(mai = c(1,1,1,1))
plot(thr$thrValues[thr$nNodesAG > 0]/OCN$CM$A,
thr$nNodesAG[thr$nNodesAG > 0], log = "xy",
xlab = "Relative area threshold", ylab = "Number of AG nodes")
par(old.par)
```

landscape_OCN

Generate 3D landscape from an Optimal Channel Network

Description

Function that calculates the elevation field generated by the OCN and the partition of the domain into different catchments.

Usage

```
landscape_OCN(OCN, slope0 = 1, zMin = 0, optimizeDZ = FALSE,
optimMethod = "BFGS", optimControl = list(maxit = 100 *
length(OCN$FD$outlet), trace = 1), displayUpdates = 0)
```

Arguments

OCN	List as produced by create_OCN .
slope0	slope of the outlet pixel (in elevation units/planar units).
zMin	Elevation of the lowest pixel (in elevation units).
optimizeDZ	If TRUE, when there are multiple catchments, minimize differences in elevation at the catchment borders by lifting catchments, while respecting zMin. If FALSE, all outlet pixels have elevation equal to zMin.

optimMethod	Optimization method used by function <code>optim</code> (only used if <code>optimizedZ = TRUE</code>).
optimControl	List of control parameters used by function <code>optim</code> (only used if <code>optimizedZ = TRUE</code>).
displayUpdates	State if updates are printed on the console while <code>landscape_OCN</code> runs. <ul style="list-style-type: none"> 0 No update is given. 1 Concise updates are given. 2 More extensive updates are given (this might slow down the total function runtime). <p>Note that the display of updates during optimization of elevations (when <code>optimizedZ = TRUE</code>) is controlled by parameter <code>optimControl\$trace</code>.</p>

Details

The function features an algorithm (which can be activated via the optional input `optimizedZ`) that, given the network configuration and a `slope0` value, finds the elevation of `OCN$nOutlet - 1` outlets relative to the elevation of the first outlet in vectors `outletSide`, `outletPos` such that the sum of the absolute differences elevation of neighboring pixels belonging to different catchments is minimized. Such objective function is minimized by means of function `optim`. The absolute elevation of the outlet pixels (and, consequently, of the whole lattice) is finally attributed by imposing `OCNFDZ >= zMin`. Note that, due to the high dimensionality of the problem, convergence of the optimization algorithm is not guaranteed for large `OCN$nOutlet` (say, `OCN$nOutlet > 10`).

Value

A list that contains all objects contained in `OCN`, in addition to the objects listed below. A new sublist `CM`, containing variables at the catchment aggregation levels, is created.

<code>FD\$slope</code>	Vector (of length <code>OCN\$FD\$nNodes</code>) of slope values (in elevation units/planar units) for each FD pixel, as derived by the slope/area relationship.
<code>FD\$leng</code>	Vector (of length <code>OCN\$FD\$nNodes</code>) of pixel lengths. <code>OCN\$FD\$leng[i] = OCN\$FD\$cellsize</code> if flow direction in <code>i</code> is horizontal or vertical; <code>OCN\$FD\$leng[i] = OCN\$FD\$cellsize*sqrt(2)</code> if flow direction in <code>i</code> is diagonal.
<code>FD\$toCM</code>	Vector (of length <code>OCN\$FD\$nNodes</code>) with catchment index values for each FD pixel. Example: <code>OCN\$FD\$toCM[i] = j</code> if pixel <code>i</code> drains into the outlet whose location is defined by <code>outletSide[j]</code> , <code>outletPos[j]</code> .
<code>FD\$XDraw</code>	When <code>periodicBoundaries = TRUE</code> , it is a vector (of length <code>OCN\$FD\$nNodes</code>) with real X coordinate of FD pixels. If <code>periodicBoundaries = FALSE</code> , it is equal to <code>OCN\$FD\$X</code> .
<code>FD\$YDraw</code>	When <code>periodicBoundaries = TRUE</code> , it is a vector (of length <code>OCN\$FD\$nNodes</code>) with real Y coordinate of FD pixels. If <code>periodicBoundaries = FALSE</code> , it is equal to <code>OCN\$FD\$Y</code> .
<code>FD\$Z</code>	Vector (of length <code>OCN\$FD\$nNodes</code>) of elevation values for each FD pixel. Values are calculated by consecutive implementation of the slope/area relationship along upstream paths.
<code>CM\$A</code>	Vector (of length <code>OCN\$nOutlet</code>) with values of drainage area (in square planar units) for each of the catchments identified by the corresponding <code>OCN\$FD\$outlet</code> .

CM\$W	Adjacency matrix (OCN\$nOutlet by OCN\$nOutlet) at the catchment level. Two catchments are connected if they share a border. Note that this is not a flow connection. Unlike the adjacency matrices at levels FD, RN, AG, this matrix is symmetric. It is a spam object.
CM\$XContour (CM\$Y_contour)	List with number of objects equal to OCN\$FD\$nOutlet. Each object <i>i</i> is a list with X (Y) coordinates of the contour of catchment <i>i</i> for use in plots with <code>exactDraw = FALSE</code> (see functions draw_contour_OCN , draw_thematic_OCN). If catchment <i>i</i> is constituted by regions that are only connected through a diagonal flow direction, <code>CM\$XContour[[i]]</code> (<code>CM\$Y_contour[[i]]</code>) contains as many objects as the number of regions into which catchment <i>i</i> is split.
CM\$XContourDraw (CM\$YContourDraw)	List with number of objects equal to OCN\$FD\$nOutlet. Each object <i>i</i> is a list with X (Y) coordinates of the contour of catchment <i>i</i> for use in plots with <code>exactDraw = TRUE</code> (see functions draw_contour_OCN , draw_thematic_OCN). If catchment <i>i</i> is constituted by regions that are only connected through a diagonal flow direction, <code>CM\$XContourDraw[[i]]</code> (<code>CM\$YContourDraw[[i]]</code>) contains as many objects as the number of regions into which catchment <i>i</i> is split.
OptList	List of output parameters produced by the optimization function optim (only present if <code>optimizedZ = TRUE</code>).

Finally, `slope0` and `zMin` are passed to the list as they were included in the input.

Examples

```
# 1) draw 2D elevation map of a 20x20 OCN with default options
OCN2 <- landscape_OCN(OCN_20)
```

```
# 2) generate a 100x50 OCN; assume that the pixel resolution is 200 m
# (the total catchment area is 20 km2)
set.seed(1)
OCN <- create_OCN(100, 50, cellsize = 200,
displayUpdates = 0) # this takes about 40 s
# use landscape_OCN to derive the 3D landscape subsumed by the OCN
# by assuming that the elevation and slope at the outlet are 200 m
# and 0.0075, respectively
OCN <- landscape_OCN(OCN, zMin = 200, slope0 = 0.0075)
# draw 2D and 3D representations of the landscape
draw_elev2D_OCN(OCN)
draw_elev3D_OCN(OCN)
draw_elev3Drg1_OCN(OCN)
```

```
# 3) generate a 100x50 OCN with 4 outlets
set.seed(1)
OCN <- create_OCN(100, 50, cellsize = 200,
nOutlet = 4, displayUpdates = 0) # this takes about 40 s
# use landscape_OCN and optimize elevation of outlets
OCN <- landscape_OCN(OCN, slope0 = 0.0075,
```

```
optimizedZ = TRUE)
# display elevation of outlets and 2D elevation map
OCN$FD$Z[OCN$FD$outlet]
draw_elev2D_OCN(OCN)
```

OCN_20

Example of small OCN

Description

A network built on a 20x20 lattice obtained by executing `set.seed(1); create_OCN(20, 20)`.

Usage

```
data(OCN_20)
```

Format

A list. See [create_OCN](#) documentation for details.

OCN_250_PB

Example of single-outlet OCN with periodic boundaries

Description

A network built on a 250x250 lattice obtained by executing `set.seed(2); create_OCN(250, 250, periodicBoundaries = TRUE)`.

Usage

```
data(OCN_250_PB)
```

Format

A list. See [create_OCN](#) documentation for details.

`OCN_250_T`*Example of single-outlet OCN*

Description

A network built on a 250x250 lattice obtained by executing `set.seed(2); create_OCN(250, 250, typeInitialState = "T")`.

Usage

```
data(OCN_250_T)
```

Format

A list. See [create_OCN](#) documentation for details.

`OCN_300_4out`*Example of multiple-outlet OCN*

Description

A network built on a 300x300 lattice obtained by executing `set.seed(5); create_OCN(300, 300, nOutlet = 4, outletSide = c("S", "N", "W", "E"), outletPos = c(1, 300, 149, 150), typeInitialState = "V", cellsize = 50)`.

Usage

```
data(OCN_300_4out)
```

Format

A list. See [create_OCN](#) documentation for details.

OCN_300_4out_PB_hot *Example of multiple-outlet OCN with periodic boundaries*

Description

A network built on a 300x300 lattice obtained by executing `set.seed(5); create_OCN(300,300,nOutlet = 4,outletSide = c("S","N","W","E"),outletPos = c(1,300,149,150),typeInitialState = "V",periodicBoundaries = TRUE,cellsize = 50,coolingRate = 0.5,initialNoCoolingPhase = 0.1)`.

Usage

```
data(OCN_300_4out_PB_hot)
```

Format

A list. See [create_OCN](#) documentation for details.

OCN_4 *Example of small OCN*

Description

A network built on a 4x4 lattice for illustrative purposes.

Usage

```
data(OCN_4)
```

Format

A list. See [create_OCN](#) documentation for details.

Details

Despite its name, this network is not an OCN: indeed, it has been generated manually and not via [create_OCN](#).

OCN_400_Allout	<i>Example of OCN with all perimetric pixels as outlets</i>
----------------	---

Description

A network built on a 400x400 lattice obtained by executing `set.seed(8); create_OCN(400, 400, nOutlet = "All", cellsize = 50)`.

Usage

```
data(OCN_400_Allout)
```

Format

A list. See [create_OCN](#) documentation for details.

OCN_to_igraph	<i>Transform OCN into igraph object</i>
---------------	---

Description

Function that transforms an OCN into an igraph object.

Usage

```
OCN_to_igraph(OCN, level)
```

Arguments

OCN	List as produced by aggregate_OCN .
level	Aggregation level at which the OCN is converted into an igraph object. It must be equal to either "FD", "RN" or "AG".

Value

An igraph object.

Examples

```
# 1) transform a 20x20 OCN, at the AG level, into a graph object
OCN <- aggregate_OCN(landscape_OCN(OCN_20), thrA = 4)
g <- OCN_to_igraph(OCN, level = "AG")
plot(g, layout = matrix(c(OCN$AG$X, OCN$AG$Y), ncol = 2, nrow = OCN$AG$nNodes))
```

OCN_to_SSN	<i>Transform OCN into SSN object</i>
------------	--------------------------------------

Description

Function that transforms an OCN into a `SpatialStreamNetwork` object. It is analogous to function `createSSN` from package `SSN`.

Usage

```
OCN_to_SSN(OCN, level, obsDesign,
           predDesign = noPoints, path, importToR = FALSE)
```

Arguments

OCN	List as produced by <code>aggregate_OCN</code> .
level	Aggregation level at which the OCN is converted into a <code>SpatialStreamNetwork</code> object. It must be equal to either "FD", "RN" or "AG".
obsDesign	Same as the argument of the same name in <code>createSSN</code> . Note that the length of the argument of the design function must be equal to <code>OCN\$N_outlet</code> .
predDesign	Same as the argument of the same name in <code>createSSN</code> . Note that, if a design function is specified, the length of its argument must be equal to <code>OCN\$N_outlet</code> .
path	Same as the argument of the same name in <code>createSSN</code> .
importToR	Same as the argument of the same name in <code>createSSN</code> .

Details

The generated `SpatialStreamNetwork` object consists of `OCN$N_outlet` networks. Note that an error is thrown if, at the selected aggregation level, at least one of these networks is degenerate (i.e. it has less than two nodes). This is typically the case for OCNs generated with option `N_outlet = "All"`.

If `OCN$PeriodicBoundaries == FALSE`, nodes' locations in the `SpatialStreamNetwork` object are given by the lattice coordinates (i.e. `OCN$level$X`, `OCN$level$Y`); if `OCN$PeriodicBoundaries == TRUE`, real coordinates are used (i.e. those defined by `OCNFDX_draw`, `OCNFDY_draw`, see `landscape_OCN`).

Value

A `SpatialStreamNetwork` object if `importToR` is `TRUE`, otherwise `NULL`.

Examples

```
# transform a 20x20 single-outlet OCN (aggregated at the AG level)
# into a SSN object and plot it
OCN <- aggregate_OCN(landscape_OCN(OCN_20), thrA = 4)
ssn1 <- OCN_to_SSN(OCN, "AG", obsDesign = SSN::poissonDesign(10),
path=paste(tempdir(),"/OCN.ssn", sep = ""), importToR = TRUE)
plot(ssn1)

# 1) create a 50x50 OCN with two outlets and periodic boundaries;
set.seed(1)
OCN <- create_OCN(50, 50, nOutlet = 2, outletSide = c("S", "N"),
outletPos = c(1, 50), periodicBoundaries = TRUE)
# aggregate the OCN;
OCN <- aggregate_OCN(landscape_OCN(OCN))
# transform it into a SSN object aggregated at the RN level;
ssn2 <- OCN_to_SSN(OCN, "RN", obsDesign = SSN::binomialDesign(c(10, 10)),
path = paste(tempdir(),"/OCN2.ssn", sep = ""), importToR = TRUE)
# and plot the SSN object; it is constituted by two networks,
# and nodes' coordinates are the "real" ones
old.par <- par(no.readonly = TRUE)
par(mai = c(1, 1, 1, 1))
plot(ssn2, xlab = "X", ylab = "Y")
par(old.par)
```

paths_OCN

Calculate paths between nodes in an Optimal Channel Network

Description

Function that determines upstream and downstream paths and path lengths between any nodes of the network at the aggregated level.

Usage

```
paths_OCN(OCN, pathsRN = FALSE, includeDownstreamNode = FALSE)
```

Arguments

OCN	List as produced by aggregate_OCN .
pathsRN	Logical. If TRUE paths and path lengths at the RN level are copied to the output list. If FALSE, only path lengths at the RN level are copied to the output list.
includeDownstreamNode	Logical. If TRUE, path lengths include the length of the edge departing from the last downstream node of the path.

Value

A list that contains all objects contained in OCN, in addition to the objects listed below.

RN\$downstreamPath

(only present if pathsRN = TRUE) List (of length OCN\$RN\$nNodes) whose object i is a list (of length OCN\$RN\$nNodes). If nodes i and j are connected by a downstream path, then $\text{RN\$downstreamPath}[[i]][[j]]$ is a vector containing the indices of the nodes constituting such path (i and j are included). If i and j are not connected by a downstream path, then $\text{RN\$downstreamPath}[[i]][[j]] = \emptyset$.

RN\$downstreamPathLength

Sparse matrix (OCN\$RN\$nNodes by OCN\$RN\$nNodes) containing length of paths between nodes that are connected by a downstream path; if i and j are not connected by a downstream path, then $\text{RN\$downstreamPathLength}[i, j] = \emptyset$. Note that $\text{RN\$downstreamPathLength}[i, i] = \emptyset$ if $\text{includeDownstreamNode} = \text{FALSE}$; alternatively, it is $\text{RN\$downstreamPathLength}[i, i] = \text{OCN\$RN\$leng}[i]$. It is a [spam](#) object.

AG\$downstreamPath

List (of length OCN\$AG\$nNodes) whose object i is a list (of length OCN\$AG\$nNodes). If nodes i and j are connected by a downstream path, then $\text{AG\$downstreamPath}[[i]][[j]]$ is a vector containing the indices of the nodes constituting such path (i and j are included). If i and j are not connected by a downstream path, then $\text{AG\$downstreamPath}[[i]][[j]] = \emptyset$.

AG\$downstreamPathLength

Sparse matrix (OCN\$AG\$nNodes by OCN\$AG\$nNodes) containing length of paths between nodes that are connected by a downstream path; if i and j are not connected by a downstream path, then $\text{AG\$downstreamPathLength}[i, j] = \emptyset$. Note that $\text{AG\$downstreamPathLength}[i, i] = \emptyset$ if $\text{includeDownstreamNode} = \text{FALSE}$; alternatively, it is $\text{AG\$downstreamPathLength}[i, i] = \text{OCN\$AG\$leng}[i]$. It is a [spam](#) object.

AG\$downstreamLengthUnconnected

Sparse matrix (OCN\$AG\$nNodes by OCN\$AG\$nNodes). $\text{AG\$downstreamLengthUnconnected}[i, j]$ is the length of the downstream portion of a path joining node i to j if i and j are not connected by a downstream path. Specifically, $\text{AG\$downstreamLengthUnconnected}[i, j] = \text{AG\$downstreamPathLength}[i, k]$, where k is a node such that there exist a downstream path from i to k and from j to k , and these paths are the shortest possible. Note that the length of the upstream portion of the path joining i to j is given by $\text{AG\$downstreamLengthUnconnected}[j, i]$. If instead i and j are joined by a downstream path, then $\text{AG\$downstreamLengthUnconnected}[i, j] = \emptyset$. It is a [spam](#) object.

Examples

```
# 1) Calculate paths between nodes of an OCN
OCN <- paths_OCN(aggregate_OCN(landscape_OCN(OCN_20), thrA = 4))

# 2) Display distance to outlet (at the RN level) along the main stem
# of an OCN
OCN <- aggregate_OCN(landscape_OCN(OCN_250_T)) # this takes some seconds
```

```

OCN <- paths_OCN(OCN, pathsRN = TRUE) # this takes some seconds

distanceToOutlet <- OCN$RN$downstreamPathLength[,OCN$RN$outlet]
farthestNode <- which(distanceToOutlet == max(distanceToOutlet))
mainStem <- OCN$RN$downstreamPath[[farthestNode]][[OCN$RN$outlet]]
theme <- rep(NaN, OCN$RN$nNodes)
theme[mainStem] <- distanceToOutlet[mainStem]

draw_thematic_OCN(theme, OCN)
title("Distance to outlet along the main stem [pixel units]")

```

rivergeometry_OCN *River geometry of an Optimal Channel Network*

Description

Function that calculates river width, depth and water velocity by applying Leopold's scaling relationships to nodes at the RN and AG levels.

Usage

```

rivergeometry_OCN(OCN, widthMax = 1, depthMax = 1,
  velocityMax = 1, expWidth = NaN, expDepth = NaN,
  expVelocity = NaN)

```

Arguments

OCN	List as produced by aggregate_OCN .
widthMax	Maximum river width allowed. If nOutlet = 1, it corresponds to the width at the outlet node.
depthMax	Maximum river depth allowed. If nOutlet = 1, it corresponds to the depth at the outlet node.
velocityMax	Maximum water velocity allowed. If nOutlet = 1, it corresponds to the water velocity at the outlet node.
expWidth, expDepth, expVelocity	Exponents for the power law relationship between river width, depth, water velocity and contributing area. If none of expWidth, expDepth, expVelocity is specified by the user, the values expWidth = 0.5, expDepth = 0.4, expDepth = 0.1 proposed by Leopold and Maddock [1953] are used. It is possible to specify two out of these three exponents, provided that each of them lies in the range (0; 1) and their sum is lower than one. In this case, the missing exponent is calculated as the complement to one of the sum of the two values provided. If all three exponents are specified by the user, their sum must be equal to one.

Details

The values of contributing area used to evaluate river geometry at the AG level are equal to $0.5 * (OCN\$AG\$A + OCN\$AG\$Areach)$. See also [aggregate_OCN](#).

See also Leopold, L. B., & Maddock, T. (1953). *The hydraulic geometry of stream channels and some physiographic implications* (Vol. 252). US Government Printing Office.

Value

A list that contains all objects contained in OCN, in addition to the objects listed below.

RN\$width	Vector (of length OCN\$RN\$nNodes) of river width values for every RN node.
RN\$depth	Vector (of length OCN\$RN\$nNodes) of river depth values for every RN node.
RN\$velocity	Vector (of length OCN\$RN\$nNodes) of water velocity values for every RN node.
AG\$width	Vector (of length OCN\$AG\$nNodes) of river width values for every AG node.
AG\$depth	Vector (of length OCN\$AG\$nNodes) of river depth values for every AG node.
AG\$velocity	Vector (of length OCN\$AG\$nNodes) of water velocity values for every AG node.

Finally, widthMax, depthMax, velocityMax, expWidth, expDepth, expVelocity are added to the list.

Examples

```
# 1) Compute river geometry of a 20x20 OCN with default options
# and display river width at the RN level
OCN <- rivergeometry_OCN(aggregate_OCN(landscape_OCN(OCN_20)))
draw_thematic_OCN(OCN$RN$width,OCN)
```

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