Optimal Supply Networks I: Branching

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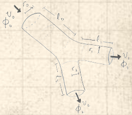
Principles of Complex Systems, Vols. 1, 2, & 3D
CSYS/MATH 300, 303, & 394, 2022–2023 | @pocsvox

Prof. Peter Sheridan Dodds | @peterdodds

Computational Story Lab | Vermont Complex Systems Center
Santa Fe Institute | University of Vermont



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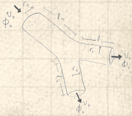

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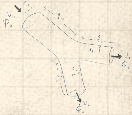
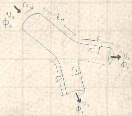
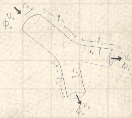


Outline



Optimal supply networks

What's the best way to distribute stuff?



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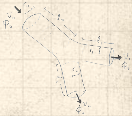

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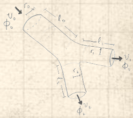

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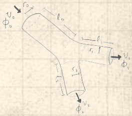

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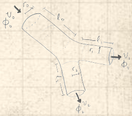

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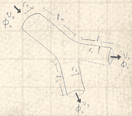

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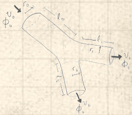
- Supply and Collection are equivalent problems

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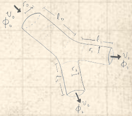
Single source optimal supply

Basic question for distribution/supply networks:

- How does flow behave given cost:

$$C = \sum_j I_j^\gamma Z_j$$

  where
  I_j = current on link j
  and
  Z_j = link j's impedance.



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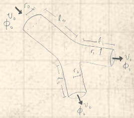
- Example: $\gamma = 2$ for electrical networks.



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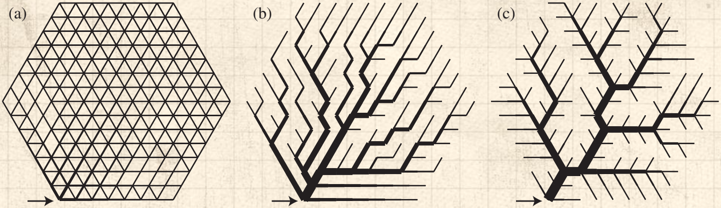


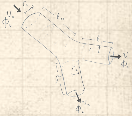
(a) $\gamma > 1$: Braided (bulk) flow

(b) $\gamma < 1$: Local minimum: Branching flow

(c) $\gamma < 1$: Global minimum: Branching flow

- Note: This is a single source supplying a region.

From Bohn and Magnasco [3]
See also Banavar *et al.* [1]: "Topology of the Fittest Transportation Network"; focus is on presence or absence of loops—same story



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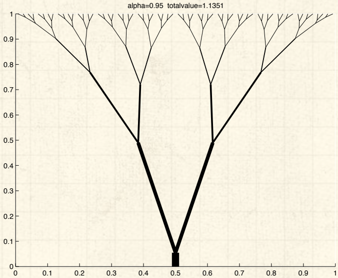
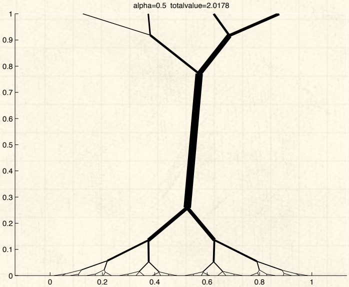
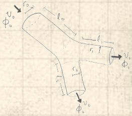
Optimal paths related to transport (Monge) problems:



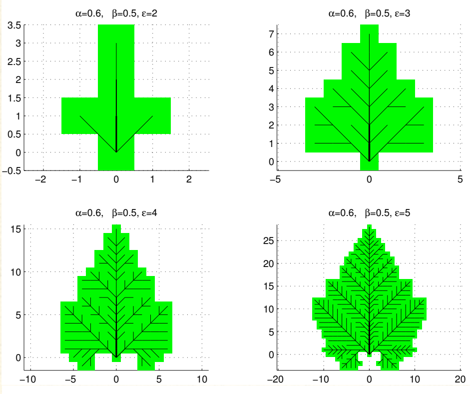


"Optimal paths related to transport problems"
Qinglan Xia,
Communications in Contemporary Mathematics, **5**, 251–279, 2003. [19]

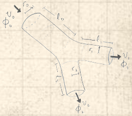


Growing networks—two parameter model: [20]

FIGURE 1. $\alpha = 0.6, \beta = 0.5$

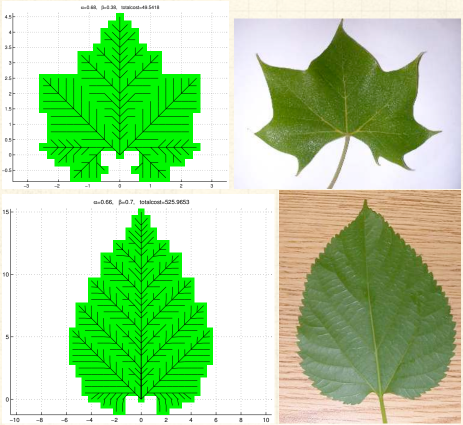


- Parameters control impedance ($0 \leq \alpha < 1$) and angles of junctions ($0 < \beta$)
- For this example: $\alpha = 0.6$ and $\beta = 0.5$

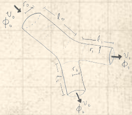


Growing networks: [20]

FIGURE 3. A maple leaf



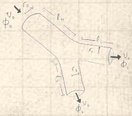
Top: $\alpha = 0.66$, $\beta = 0.38$; Bottom: $\alpha = 0.66$, $\beta = 0.70$



Single source optimal supply

An immensely controversial issue ...

- The form of natural branching networks: Random, optimal, or some combination? [6, 18, 2, 5, 4]



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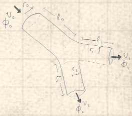

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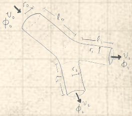

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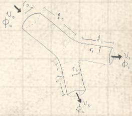

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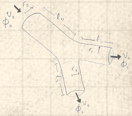
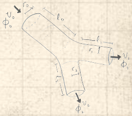
- Real networks differ in details of scaling but reasonably agree in scaling relations.



River network models

Optimality:

- Optimal channel networks [13]
- Thermodynamic analogy [14]



River network models

Optimality:

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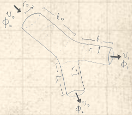
versus ...

Randomness:

- Scheidegger's directed random networks
- Undirected random networks

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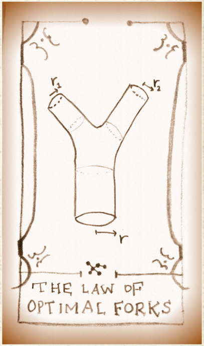
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r2
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THE LAW OF OPTIMAL FORKS

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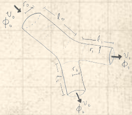
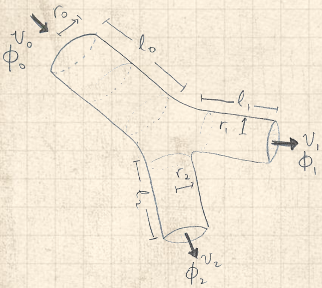


Optimization—Murray's law



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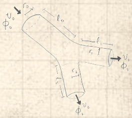
$$r_0^3 = r_1^3 + r_2^3$$

where r_0 = radius of main branch, and r_1 and r_2 are radii of sub-branches.



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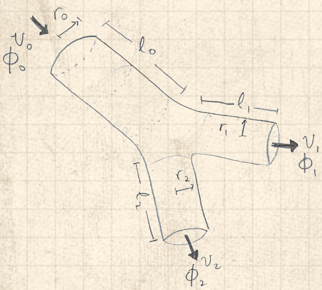

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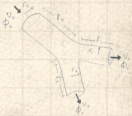

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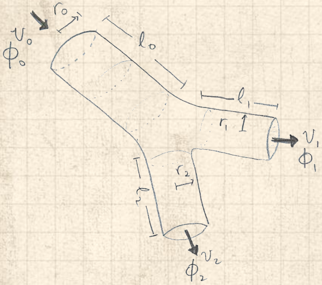

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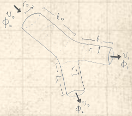
- Also found to hold for trees [12, 8] when xylem is not a supporting structure [9].



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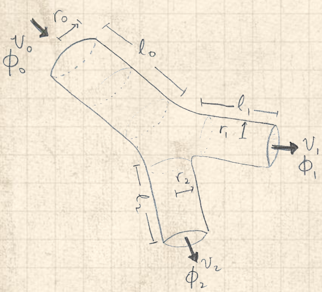

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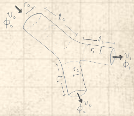
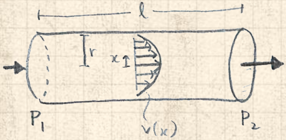
- See D'Arcy Thompson's "On Growth and Form" for background and general inspiration [15, 16].

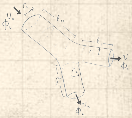


Use hydraulic equivalent of Ohm's law:

$$\Delta p = \Phi Z \Leftrightarrow V = IR$$

where Δp = pressure difference, Φ = flux.





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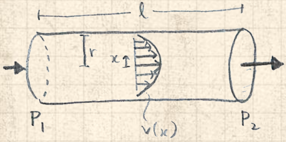
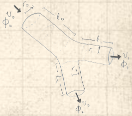


- Fluid mechanics: Poiseuille impedance for smooth Poiseuille flow in a tube of radius r and length ℓ:

$$Z = \frac{8\eta\ell}{\pi r^4}$$

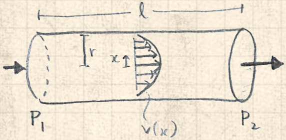
- η = dynamic viscosity (units: $ML^{-1}T^{-1}$).



- Use hydraulic equivalent of Ohm's law:

$$\Delta p = \Phi Z \Leftrightarrow V = IR$$

where Δp = pressure difference, Φ = flux.



- Fluid mechanics: Poiseuille impedance for smooth Poiseuille flow in a tube of radius r and length ℓ:

$$Z = \frac{8\eta\ell}{\pi r^4}$$

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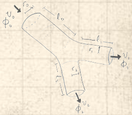
$$P_{\text{drag}} = \Phi \Delta p = \Phi^2 Z.$$



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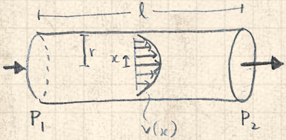

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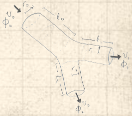
- η = dynamic viscosity (units: $ML^{-1}T^{-1}$).
- Power required to overcome impedance:

$$P_{\text{drag}} = \Phi \Delta p = \Phi^2 Z.$$

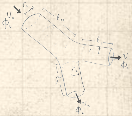
- Also have rate of energy expenditure in maintaining blood given metabolic constant c:

$$P_{\text{metabolic}} = c r^2 \ell$$



Optimization—Murray's law

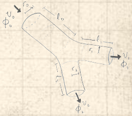
Aside on P_{drag}



Optimization—Murray's law

Aside on P_{drag}

- Work done = $F \cdot d$ = energy transferred by force F



Optimization—Murray's law

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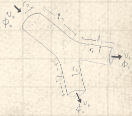
- Work done = $F \cdot d$ = energy transferred by force F
- Power = P = rate work is done = $F \cdot v$



Optimization—Murray's law

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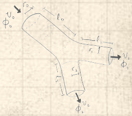
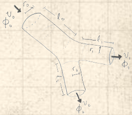
- Δp = Pressure differential = Force per unit area



Optimization—Murray's law



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Optimization—Murray's law

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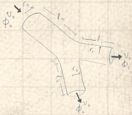
  = cross-sectional area · velocity
- S o $\Phi \Delta p$ = Force · velocity

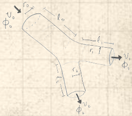


Optimization—Murray's law

Murray's law:

- Total power (cost):

$$P = P_{\text{drag}} + P_{\text{metabolic}}$$

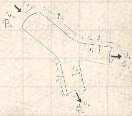


Optimization—Murray's law

Murray's law:

- Total power (cost):

$$P = P_{\text{drag}} + P_{\text{metabolic}} = \Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell$$



Optimization—Murray's law

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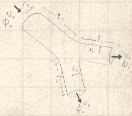
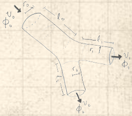
- Total power (cost):

$$P = P_{\text{drag}} + P_{\text{metabolic}} = \Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell$$

- Observe power increases linearly with ℓ



Optimization—Murray's law



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- But r's effect is nonlinear:

Optimization—Murray's law

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- Total power (cost):

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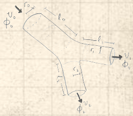


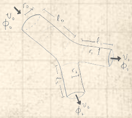
Optimization—Murray's law

Murray's law:

- Total power (cost):

$$P = P_{\text{drag}} + P_{\text{metabolic}} = \Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell$$

- Observe power increases linearly with ℓ
- But r's effect is nonlinear:
  - increasing r makes flow easier but increases metabolic cost (as r^2)
  - decreasing r decrease metabolic cost but impedance goes up (as r^{-4})

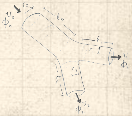


Optimization—Murray's law

Murray's law:

- Minimize P with respect to r:

$$\frac{\partial P}{\partial r} = \frac{\partial}{\partial r}\left(\Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell\right)$$



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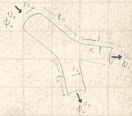
- Minimize P with respect to r:

$$\frac{\partial P}{\partial r} = \frac{\partial}{\partial r}\left(\Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell\right)$$

- Flow rates at each branching have to add up (else our organism is in serious trouble ...):

$$\Phi_0 = \Phi_1 + \Phi_2$$

where again 0 refers to the main branch and 1 and 2 refers to the offspring branches

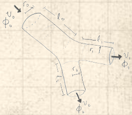


Optimization—Murray's law

Murray's law:

- Find:

$$\Phi = k r^3$$



Optimization—Murray's law

Murray's law:

- Find:

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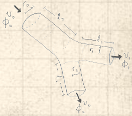
- Insert question from assignment 16



Optimization—Murray's law

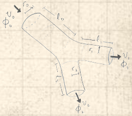
Murray's law:

- Find:

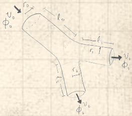
$$\Phi = kr^3$$

- Insert question from assignment 16
- All of this means we have a groovy cube-law:

$$\boxed{r_0^3 = r_1^3 + r_2^3}$$



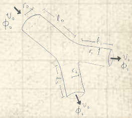
Outline



Optimization

Murray meets Tokunaga:

- Φ_ω = volume rate of flow into an order ω vessel segment

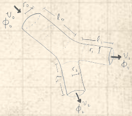


Optimization

Murray meets Tokunaga:

- Φ_ω = volume rate of flow into an order ω vessel segment
- Tokunaga picture:

$$\Phi_\omega = 2\Phi_{\omega-1} + \sum_{k=1}^{\omega-1} T_k \Phi_{\omega-k}$$



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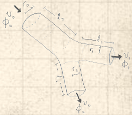
- Using $\phi_\omega = k r_\omega^3$

$$(r_\omega)^3 = 2\left(r_{\omega-1}\right)^3 + \sum_{k=1}^{\omega-1} T_k \left(r_{\omega-k}\right)^3$$



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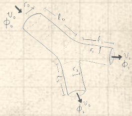
$$(r_\omega)^3 = 2\left(r_{\omega-1}\right)^3 + \sum_{k=1}^{\omega-1} T_k \left(r_{\omega-k}\right)^3$$

- Same form as:

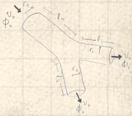
$$n_\omega = \underbrace{2 n_{\omega+1}}_{\text{generation}} + \sum_{\omega'=\omega+1}^{\Omega} \underbrace{T_{\omega'-\omega} n_{\omega'}}_{\text{absorption}}$$



Optimization

Murray meets Tokunaga:

- Find Horton ratio for vessel radius $R_r = r_\omega / r_{\omega-1}$.

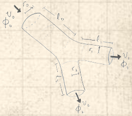


Optimization

Murray meets Tokunaga:

- Find Horton ratio for vessel radius $R_r = r_\omega / r_{\omega-1}$.
- Find R_r^3 satisfies same equation as R_n and R_v (v is for volume):

$$\boxed{R_r^3 = R_n = R_v}$$



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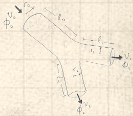
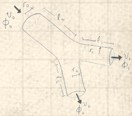
- Is there more we could do here to constrain the Horton ratios and Tokunaga constants?



Optimization

Murray meets Tokunaga:

- Isometry: $V_\omega \propto \ell_\omega^3$



Optimization

Murray meets Tokunaga:

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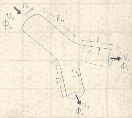
- Gives

$$\boxed{R_\ell^3 = R_r^3 = R_n = R_v}$$



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Murray meets Tokunaga:

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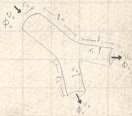
- We need one more constraint ...



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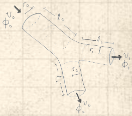
- We need one more constraint ...
- West *et al.* (1997) [18] achieve similar results following Horton's laws (but this work is a disaster).



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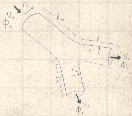
- We need one more constraint ...
- West *et al.* (1997) [18] achieve similar results following Horton's laws (but this work is a disaster).
- So does Turcotte *et al.* (1998) [17] using Tokunaga (sort of).

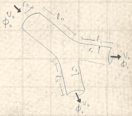


References I

[1] J. R. Banavar, F. Colaiori, A. Flammini, A. Maritan, and A. Rinaldo.
Topology of the fittest transportation network.
Phys. Rev. Lett., 84:4745–4748, 2000. pdf

[2] J. R. Banavar, A. Maritan, and A. Rinaldo.
Size and form in efficient transportation networks.
Nature, 399:130–132, 1999. pdf

[3] S. Bohn and M. O. Magnasco.
Structure, scaling, and phase transition in the optimal transport network.
Phys. Rev. Lett., 98:088702, 2007. pdf

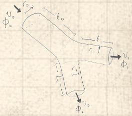


References II

[4] P. S. Dodds.
Optimal form of branching supply and collection networks.
Phys. Rev. Lett., 104(4):048702, 2010. pdf

[5] P. S. Dodds and D. H. Rothman.
Geometry of river networks. I. Scaling, fluctuations, and deviations.
Physical Review E, 63(1):016115, 2001. pdf

[6] J. W. Kirchner.
Statistical inevitability of Horton's laws and the apparent randomness of stream channel networks.
Geology, 21:591–594, 1993. pdf



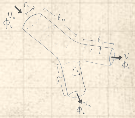
References III

[7] P. La Barbera and R. Rosso.
Reply.
Water Resources Research, 26(9):2245–2248, 1990. pdf

[8] K. A. McCulloh, J. S. Sperry, and F. R. Adler.
Water transport in plants obeys Murray's law.
Nature, 421:939–942, 2003. pdf

[9] K. A. McCulloh, J. S. Sperry, and F. R. Adler.
Murray's law and the hydraulic vs mechanical functioning of wood.
Functional Ecology, 18:931–938, 2004. pdf

[10] C. D. Murray.
The physiological principle of minimum work applied to the angle of branching of arteries.
J. Gen. Physiol., 9(9):835–841, 1926. pdf

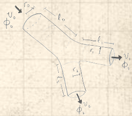


References IV

[11] C. D. Murray.
The physiological principle of minimum work. I. The vascular system and the cost of blood volume.
Proc. Natl. Acad. Sci., 12:207–214, 1926. pdf

[12] C. D. Murray.
A relationship between circumference and weight in trees and its bearing on branching angles.
J. Gen. Physiol., 10:725–729, 1927. pdf

[13] I. Rodríguez-Iturbe and A. Rinaldo.
Fractal River Basins: Chance and Self-Organization.
Cambridge University Press, Cambrigde, UK, 1997.



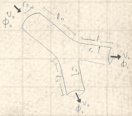
References V

[14] A. E. Scheidegger.
Theoretical Geomorphology.
Springer-Verlag, New York, third edition, 1991.

[15] D. W. Thompson.
On Growth and Form.
Cambridge University Pres, Great Britain, 2nd edition, 1952.

[16] D. W. Thompson.
On Growth and Form — Abridged Edition.
Cambridge University Press, Great Britain, 1961.

[17] D. L. Turcotte, J. D. Pelletier, and W. I. Newman.
Networks with side branching in biology.
Journal of Theoretical Biology, 193:577–592, 1998.
pdf



References VI

[18] G. B. West, J. H. Brown, and B. J. Enquist.
A general model for the origin of allometric scaling laws in biology.
Science, 276:122–126, 1997. pdf

[19] Q. Xia.
Optimal paths related to transport problems.
Communications in Contemporary Mathematics, 5:251–279, 2003. pdf

[20] Q. Xia.
The formation of a tree leaf.
ESAIM: Control, Optimisation and Calculus of Variations, 13:359–377, 2007. pdf