THE ECONOMICS OF INLAND WATERWAY TRANSPORTATION

by

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ABSTRACT

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Submitted to the Department of Civil Engineering on August 27, 1972 in partial fulfillment of the requirements for the degrees of Master of Science and Civil Engineer

This thesis illustrates the economic analysis of a production function for inland waterway transportation. An economic analysis was performed which showed that there is diminishing marginal returns to the two inputs, horsepower and barge deck area. Returns to scale are shown to be variable depending upon the waterway environment encountered. The effects of a stream current and of the existence of constraints such as a maximum length for the barge flotilla are explored. In general the effect of constraints and diminishing marginal returns and returns to scale is to yield a convex feasible region for output, thus enabling one to find specific optimal designs. The effect of a stream current is to distort the isoquants of the production function in favor of increased horsepower.

Isoquants and expansion paths are derived under varying relative costs for the inputs and it is shown that, with no constraints on the length of the barge flotilla and no stream current, the production function is linear and homogeneous. The existence of a stream current or a maximum barge length constraint transforms the production function into a linear, non-homogeneous function.

Tradeoffs between increased level of service, as defined by speed, and cost are generated as well as tradeoffs between dredging and increased investment in towboat horsepower for equal output. In the latter case, it is shown that dredging is cost-effective only for short distances or for considerable traffic on the waterway.

It is stressed that an inland waterway transport firm may experience increasing returns to scale in its production function but decreasing returns to scale in its capital stock-output relationship, called the "planning function." Ultimately, the capital stock-output relationship and its scale economies or diseconomies will determine the firm's ability to expand line-haul operations without incurring increasing inefficiency.

Finally, when actual operating data are compared with output from the production function model, the imputed costs of barge construction compare favorably with cost data from the U.S.A. and other countries.

Thesis Supervisor: Richard de Neufville

Title: Associate Professor

ACKNOWLEDGEMENTS

I want to dedicate this thesis to my parents, who always gave me the freedom to pursue my goals and aims.

I wish to acknowledge, first of all, the on-going help and guidance provided by Professor Richard de Neufville in directing the general lines of research and emphasis required during the writing of this thesis. The germ idea of the thesis must also be attributed to him, which was to explore the effects of stream current, as well as economic aspects, of the production function.

I would also like to acknowledge the help given me by "Don" Luis Javier Mira while I was in Colombia in arranging data-gathering interviews for me in Barranquilla through his contacts with Dr. Miguel Barrera.

Acknowledgement is due to the Department of Transportation, Office of the Secretariat for Policy and International Affairs, whose contract to MIT concerning the role of transportation in economic development provided my funding as a Research Assistant during 1970-71, and provided the initial area of work for this thesis. Also acknowledgement is due the MIT Civil Engineering Department for the financial support provided by a Sloan Research Traineeship during the academic year, 1971-72.

Finally, I would like to express my appreciation to the typist of this thesis, Miss Rosemary Carpenter, for her accuracy and patience amidst many time pressures.

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CHAPTER 1. INTRODUCTION

This thesis illustrates the economic analysis of a production function for water transportation which exists in an explicit equation form. This production function was derived from tow-tank tests and has been presented in the literature by Howe (6-8). This thesis uses the production function developed by Howe to perform a more extensive economic analysis which considers diminishing marginal returns to the inputs, returns to scale, the effect of stream current velocity, and constraints on the length of the barge flotilla. Expansion paths are also derived showing optimal designs for water transport, in terms of optimal ratios of horsepower to barge deck area, in light of prevailing cost and operating conditions. This analysis then generates a cost-effectiveness function which can be input into the model for choosing preferred transport technologies in a given region.

Since a production function is purely a technological relationship, independent of costs, it is therefore universally valid in any country. The production function gives a general statement of all outputs that can be obtained from all technically efficient input combinations. The specific production function developed by Howe was used to define design and operational guidelines for barge-towboat flotillas transporting cargo on inland waterways.

One must consider three basic design issues when attempting to maximize the returns from transportation investments: first, the determination of guidelines for optimal design configuration in terms of ratios of inputs to the production function; second, the specification of optimal scale of production, in light of the determining environment; and third, the changes in optimal design configuration as a result of changes in the determining environment.

By using a production function for waterway transport which exists in explicit equation form, and which relates quantitatively the engineering design variables to the output measure, say ton-miles per hour, one can determine optimal equipment sizes and configurations, in terms of ratios of inputs to the production function, for operations on a given inland waterway.

By including in the engineering production function equation, variables representing the width and the depth of the waterway, one can specify how the optimal design changes for different conditions of the waterway. For example, the existence of various constraints limits choices and distorts the expansion paths to second-best designs.

By the use of this production function in equation form, one can analyze the incremental effects of implementing any particular project on a given waterway, both in terms of the system-wide output and the system-wide public and private sector costs.

Although one may be able to separate the above three issues analytically, and even though their implementation as decisions may involve organizationally independent bodies, the overall problem is one of simultaneous optimization with respect to the characteristics of the waterway in question, such as width and depth and the parameters defining the transport equipment.

As indicated, the optimal sizing and selection of equipment such as barges and towboats depends on the depth, width, and stream velocity of the waterway. Furthermore, the optimal width and depth of a proposed waterway depend not only on the projected total volume of traffic, but also on the types of equipment that will be used, and on the velocity of the stream current. Consequently, a global optimization, where all parameters would be considered variable, would be extremely complex and expensive.

The engineering production function described in this thesis can be useful for predicting the effects of width and depth variation of the waterway on barge tow performance in terms of ton-miles per hour output and operating costs per ton-mile. It would also be useful in sizing the types of equipment, such as barges and towboats, that would be used by private operators in waterways of various widths and depths. However, a global optimization of the scale variables of the waterway would be very involved, since for each value of the depth and width of the waterway explored, one would have to optimize over all size combinations of equipment to be used. Thus, regardless of the existence or non-existence of optimal design of the waterway, the production function described herein is capable of assisting in the selection of equipment and barge-towboat flotilla make-up, so that transport requirements can be met at a minimum cost.

CHAPTER 2. DERIVATION OF THE PRODUCTION FUNCTION

Through various articles, Howe has explored the major aspects of barge-towboat technology (7,8). There are three major factors which must be taken into consideration when deriving empirical functional relationships of barge-towboat technology:

1. The resistance, R, of the barge flotilla. This will be a function of speed and barge characteristics, such as length, breadth, draft, etc.
2. The effective push, EP, which the towboat generates. This will be a function of the size of its engines, and the speed through the water.
3. The effects of the waterway environment on both the resistance of the barge flotilla and the effective push generated by the towboat. The depth and width of the waterway will affect the operation of the barge-towboat flotilla.

For any barge-towboat flotilla to proceed at constant speed on a given waterway, the basic physics of the situation dictate that the effective push of the towboat must equal the sum of the resistances acting on the barge flotilla, i.e.

$$EP = \Sigma_i R_i \qquad (2.1)$$

The horsepower of the towboat, the speed of the barge-towboat flotilla, and the characteristics of the waterway environment, such as width, depth, and velocity of the stream current, will determine the effective push of the towboat. On the other hand, barge flotilla characteristics, speed of the flotilla, and the velocity of the stream current will determine the resistance of the barge flotilla. Thus Eq. 2.1 will be able to determine the equilibrium speed for any towboat-barge flotilla combination. By the incorporation of the depth and the width of the waterway as variables directly in the expressions for R and EP, the effects on overall tow performance of waterway improvements that involve increased depth and/or width can be evaluated directly. As can be seen, the production function derives directly from Eq. 2.1.

It should be indicated that this approach to determining a production function is really only valid when one is dealing with force fields, such as in water transportation, for which well-defined physical relationships exist. No such relations really exist for road or air transport and, consequently, their production functions are much more difficult to derive.

Using the physical relationships defined by Eq. 2.1, the equilibrium tow speed relative to the water, S*, can be determined through solving the following set of equations:

$$S^* = -1.14 \text{xHP} + [1.3\ (\text{HP}^2) - 4.(\delta)\ (-1)^{\delta+1} \text{x RDRAG} - 31.82 \text{xHP} + 0.0039 \text{xHP}^2 - 0.38 \text{xHPxD}]^{0.5} / 2(\beta) \qquad (2.2)$$

where the drag resistance, RDRAG, is:

$$\text{RDRAG} = 0.0086 \text{x} (S_w{}^2) \text{ x } (D^{-1.33}) \text{ x } (52 + 0.44 - H) \text{ x}(H) \text{x}(L) \text{x}(B) + 24{,}300 + 350 \text{xHP} - 0.021\ (\text{HP})^2 \qquad (2.3)$$

and the coefficient β is defined as:

$$\beta = 0.07289 \text{ x } \exp\{1.46/(D-H)\} \text{ x } [H^{\{0.6+50/(W-B)\}}] \text{ x } (L^{0.38})\ (B^{1.19}) + 172 \qquad (2.4)$$

The barge-towboat speed relative to the ground, S, can be determined as:

$$S = S^* + (-1)^{\delta} S_w \qquad (2.5)$$

where S_w is stream current and δ is a dummy variable indicating the direction of travel (δ=0 for downstream, δ=1 for upstream).

Thus, by specifying the brake horsepower, HP, of the towboat, the overall length, L, breadth, B, and draft, H, of the barge flotilla, and the depth, D, width, W,and stream current, S_w, of the waterway, plus the direction of travel, δ, one can determine the equilibrium speed. Fixing these variables determines not only the speed of the barge-towboat flotilla, but, for a particular barge design, the cargo tonnage carried by the tow as a function of L, B, and H. Then, by definition, the rate of output of the tow in net cargo ton-miles per hour is given by:

$$TM = S\ (HP,\ L,\ B,\ H;\ D,\ W,\ S_w)\ T\ (L,\ B,\ H) \qquad (2.6)$$

This, then, is the production function for the barge-towboat flotilla, as conditioned by the characteristics of the waterway in which it operates.

The draft of the flotilla is, however, a function of the loading of the barge. If one combines the breadth and length of the barge into one design parameter, the deck area, then one can describe output in terms of only two major design inputs: brake horsepower of the towboat and deck area of the barge flotilla.

A short FORTRAN program was written for an IBM 1130 computer of 16K byte storage capacity. This program utilizes a structure of consecutive DO loops on the variables of the production function to evaluate Eqs. 2.1 to 2.6. The program outputs ton-miles per hour as a function of the user-specified inputs to the production function.

CHAPTER 3. EXPLORATION OF THE PRODUCTION FUNCTION

3.1 Introduction

This chapter explores underlying properties of the production function for water transport. The existence of diminishing marginal returns, returns to scale, the effects of stream currents, and the effects of constraints such as a maximum limit on the length of the barge flotilla, are examined.

In general the effect of constraints and diminishing marginal returns and returns to scale is to yield a convex feasible region for output, thus enabling one to find specific optimal designs. The effect of a stream current is to distort the isoquants of the production function in favor of increased horsepower. Returns to scale are shown to be variable depending upon the waterway environment encountered.

3.2 Diminishing Marginal Returns

We examined the effect on ton-miles per hour output of keeping barge deck area (in square feet) constant while varying the horsepower. The total product curves for a fixed barge deck area are strictly concave, reflecting the diminishing marginal productivity of the horsepower's input (Figure 3.1). The underlying

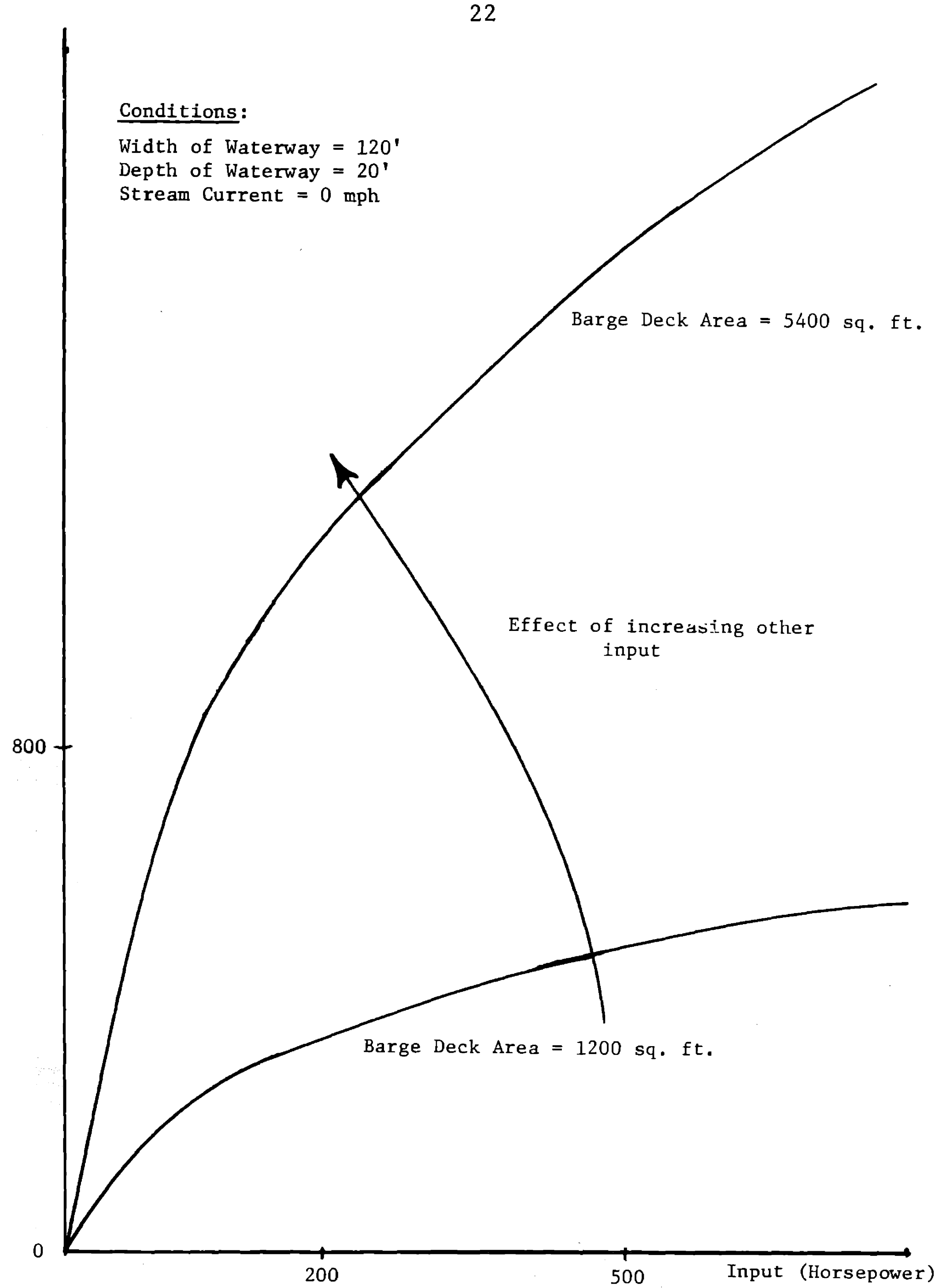


FIGURE 3.1 TYPICAL DIMINISHING MARGINAL RETURN OF WATER TRANSPORT PRODUCTION FUNCTION

technical reason for the diminishing marginal returns of ton-miles per hour of output with respect to horsepower, is that the rate of increase of equilibrium speed in still water with respect to an increment in horsepower is continually decreasing (Figure 3.2). As the speed increases, the water flow to the propeller screws of the towboat is restricted so that maximum advantage cannot be drawn from the extra horsepower. Also, the resistance of the barge flotilla increases because more water is drawn from under the flotilla, causing the barges to "squat."

3.3 Returns to Scale

The existence of increasing returns to scale for the engineering production function was explored by defining the sample activity vectors shown in Figure 3.3. These activity vectors correspond to varying ratios of horsepower to barge deck area, and thus correspond to low-, medium-, and relatively high-powered barge flotilla combinations.

It must be remembered that the phrase "returns to scale" is used to refer only to the relationships between changes in the physical quantity of output and changes in the physical quantity of all inputs simultaneously and in the same proportions. If doubling or halving all inputs always results in exactly doubling

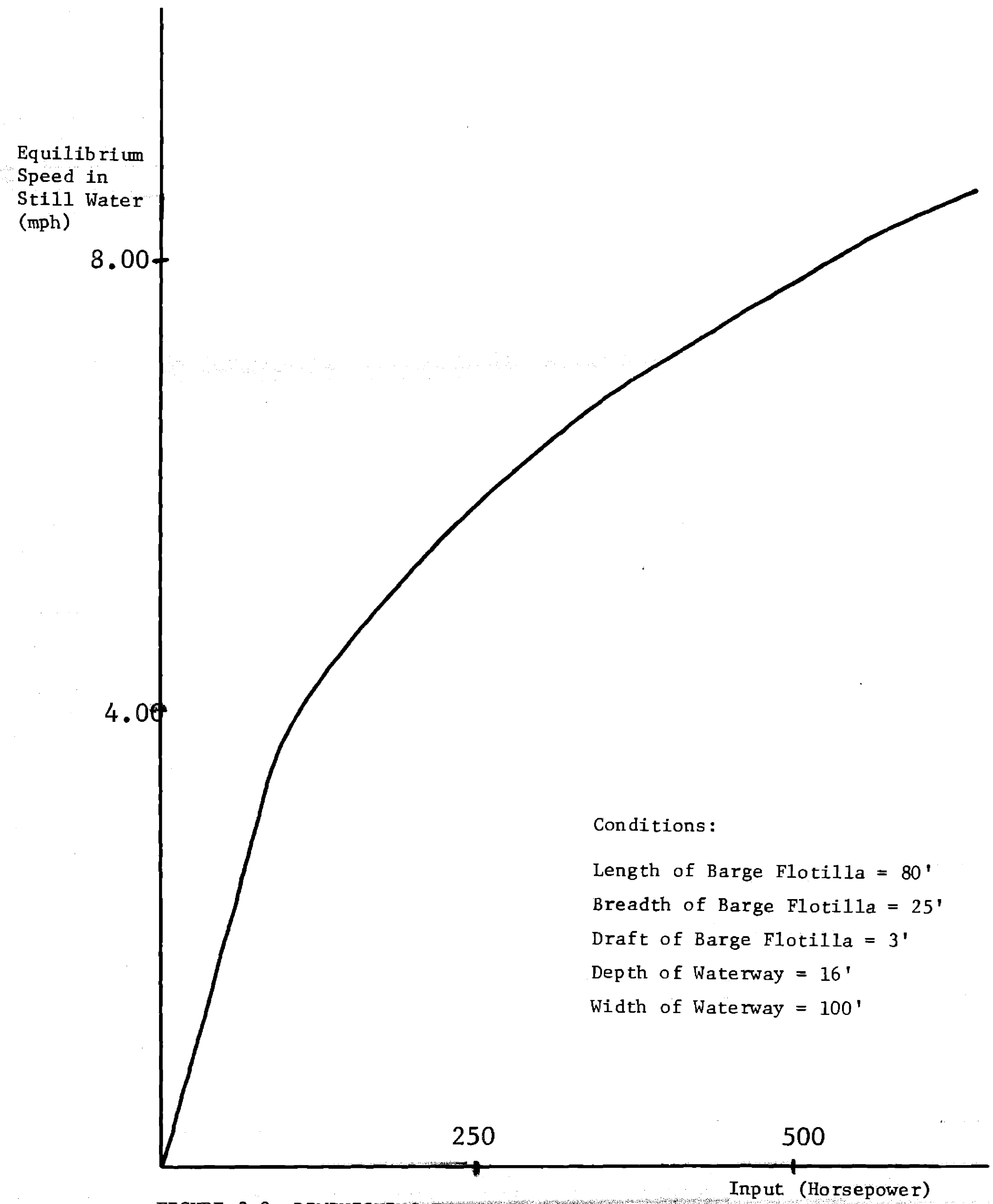


FIGURE 3.2 DIMINISHING EFFECTIVENESS OF INPUTS AS OTHER DESIGN FEATURES ARE HELD CONSTANT

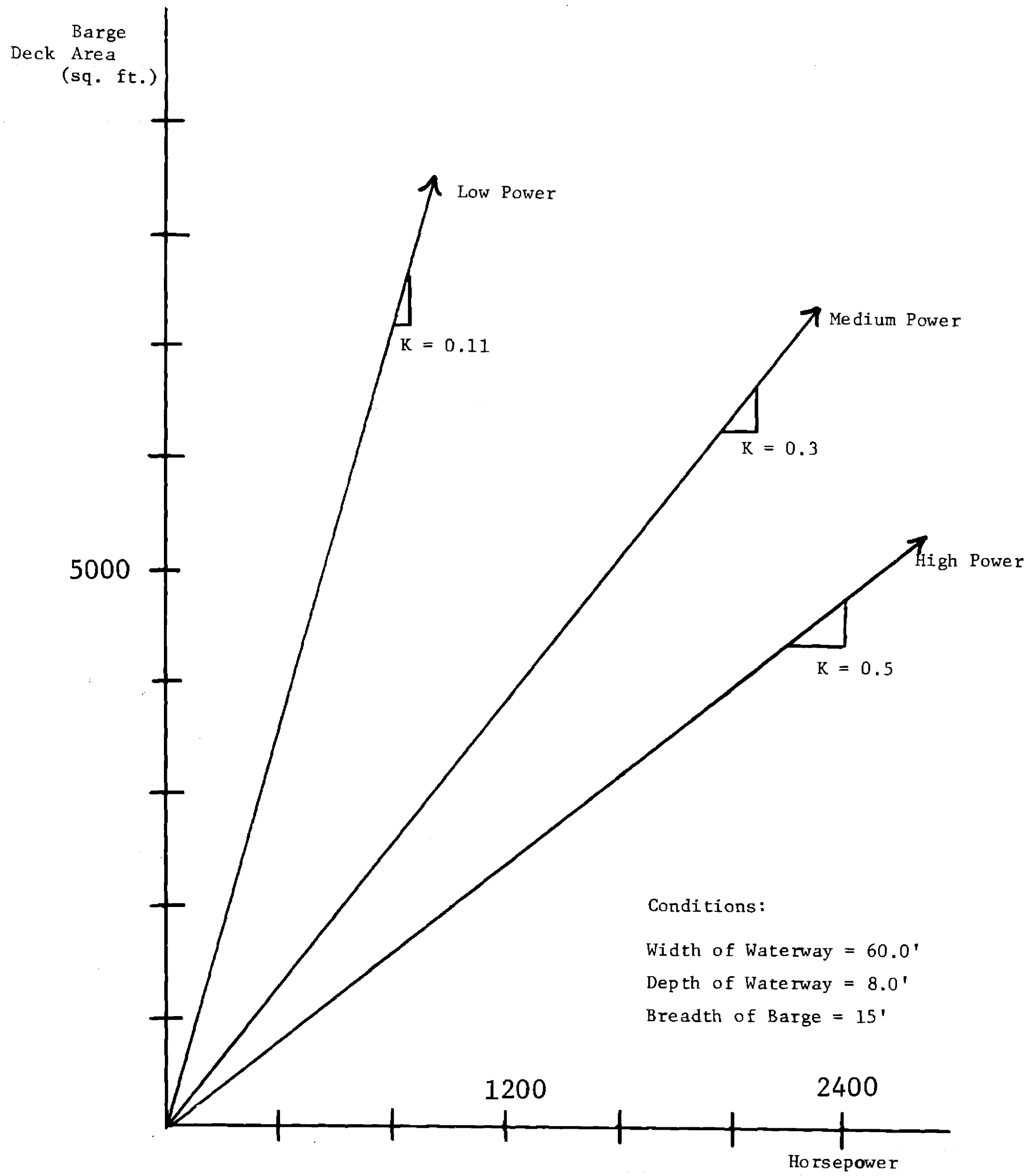


FIGURE 3.3 NOMINAL CONFIGURATIONS FOR ANALYSIS OF WATER TRANSPORT DESIGN

or halving efficient output, the production process, production function, or production technology is said to possess constant returns to scale. If doubling all inputs more than doubles output, it has increasing returns to scale; if it less than doubles output, it has decreasing returns to scale.

Figure 3.4 shows the results of the returns to scale analysis with no constraint on the maximum length of the barge flotilla. The numbers shown on the horizontal scale represent doubling, tripling, quadrupling etc. all inputs simultaneously on the lines shown. The production function, in this case, exhibits increasing returns to scale.

3.4 Generation of Total Product Curves and Isoquants

The total product curves are shown as a function of horsepower for various barge sizes at a 0-miles per hour stream current (Figure 3.5). They again show the phenomenon of diminishing marginal returns with respect to horsepower for a constant barge deck area.

The isoquants can be derived from the total product curves by plotting the total product curves at constant output levels, say 1200 ton-miles per hour. The intersection of this level with the total product curves, as at A and B, define design configurations of equal effectiveness. These are, of course, points on the

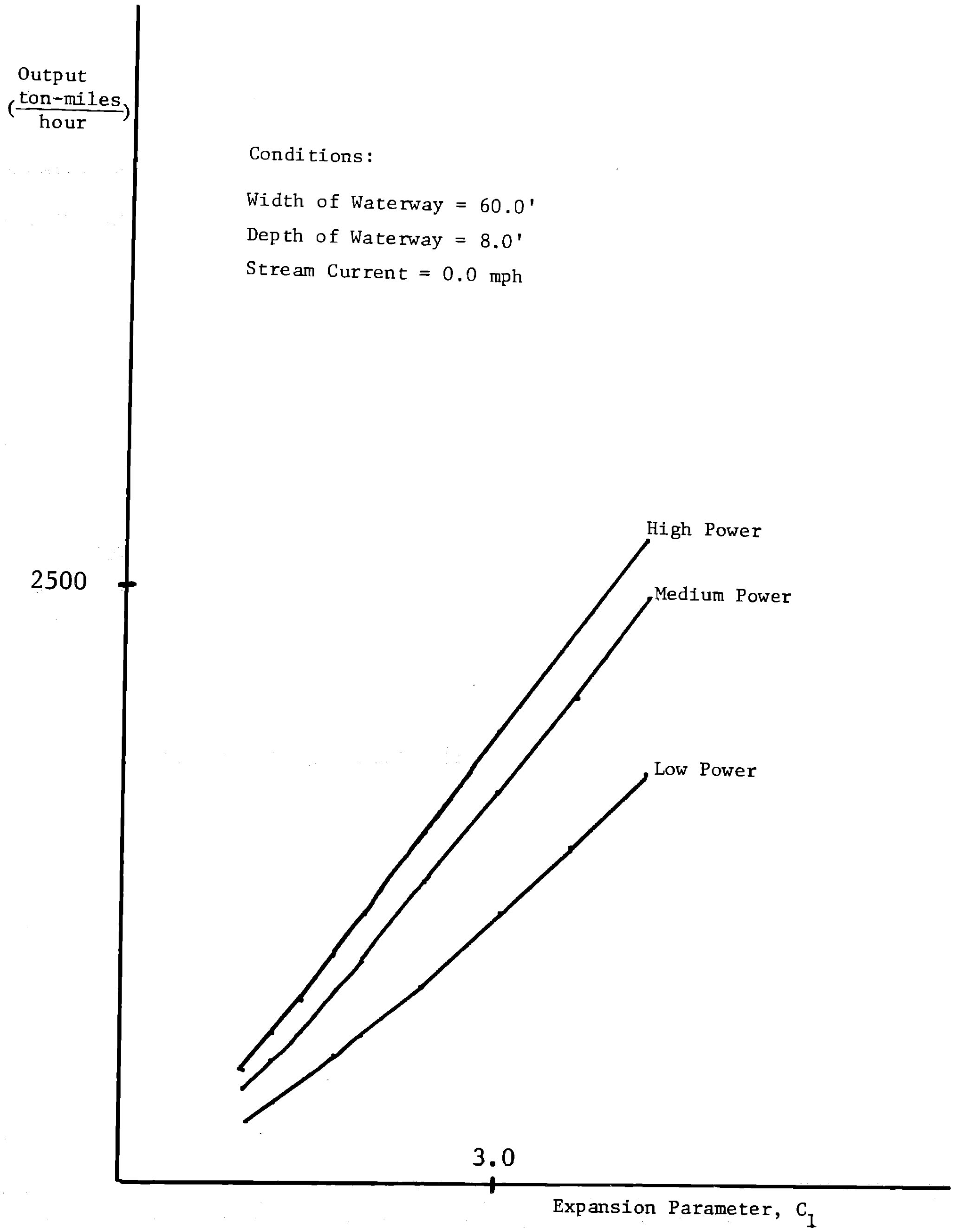


FIGURE 3.4 INCREASING RETURNS TO SCALE FOR WATER TRANSPORT (DESIGN IS C_1 [K(HORSEPOWER), BARGE DECK AREA]

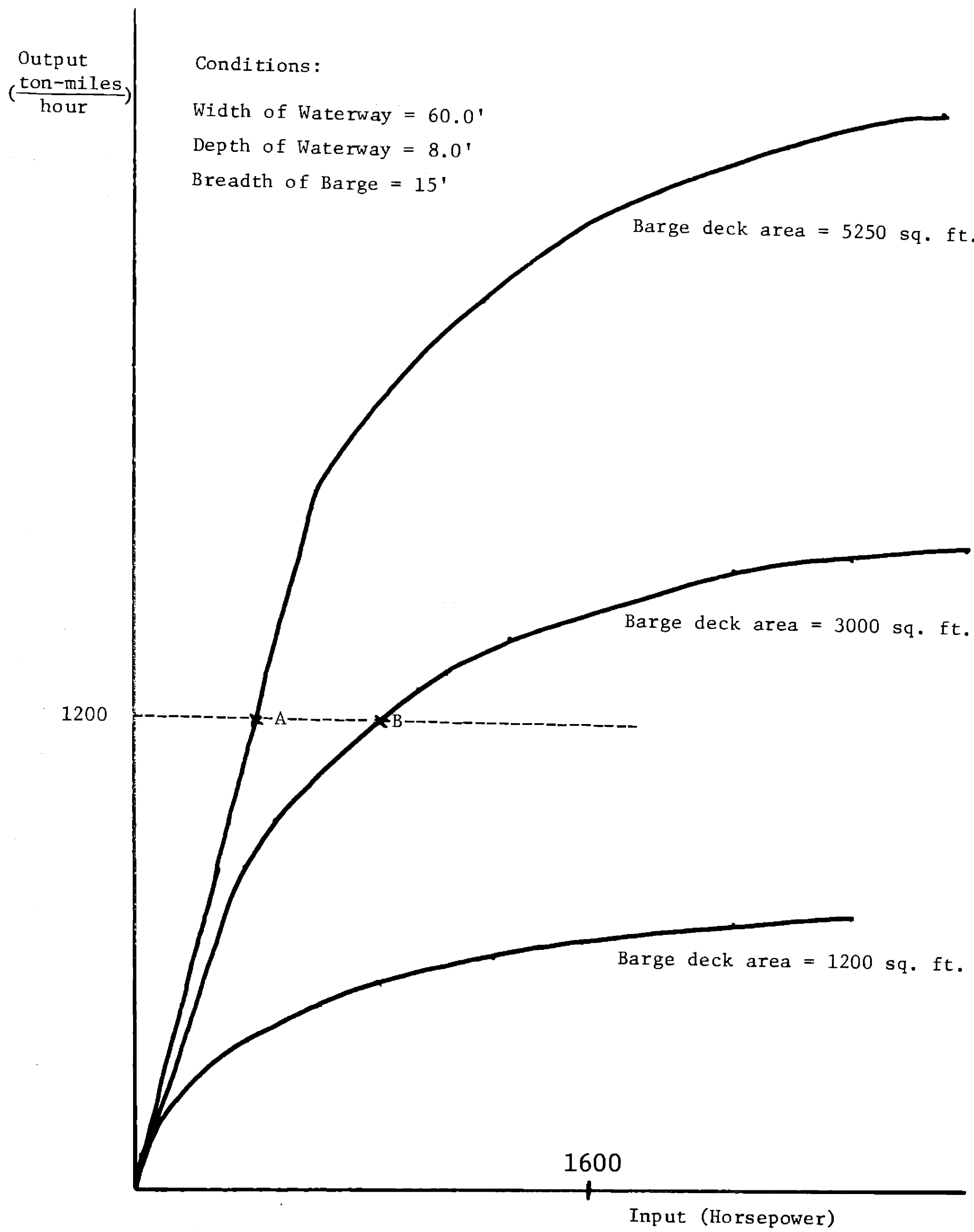


FIGURE 3.5 TOTAL PRODUCT CURVES CAN BE USED TO DETERMINE ISOQUANTS AND EQUAL EFFECTIVENESS DESIGNS

isoquants. The isoquants show the marginal rate of substitution between the horsepower and barge deck area inputs necessary to maintain a specified output level (Figure 3.6).

3.5 Derivation of Expansion Paths

For the given relative prices of the two inputs, horsepower and barge deck area, the expansion path tells us how the optimal input combination (the horsepower to square feet ratio) will vary when the capital budget increases.

For reasons of simplicity in presentation and deviation, it was assumed that the cost of 1 horsepower of engine would be equal to the cost of 1 square foot of deck area. This is shown graphically in Figure 3.7. Alternative cost ratios can, of course, be considered in the model. Points on the isocost lines represent equal capital budget expenditure outlays. The points of tangency of these isocost lines with the isoquants define the expansion path as shown in Figure 3.7. This condition of tangency is a geometric representation of the basic rule that an optimal combination of inputs requires that the ratio of their marginal products be equal to the ratio of their prices.

It can be seen from Figure 3.7 that the expansion path shown approximates a straight line through the origin of the graph. This means that, given the prices of the inputs, and the same

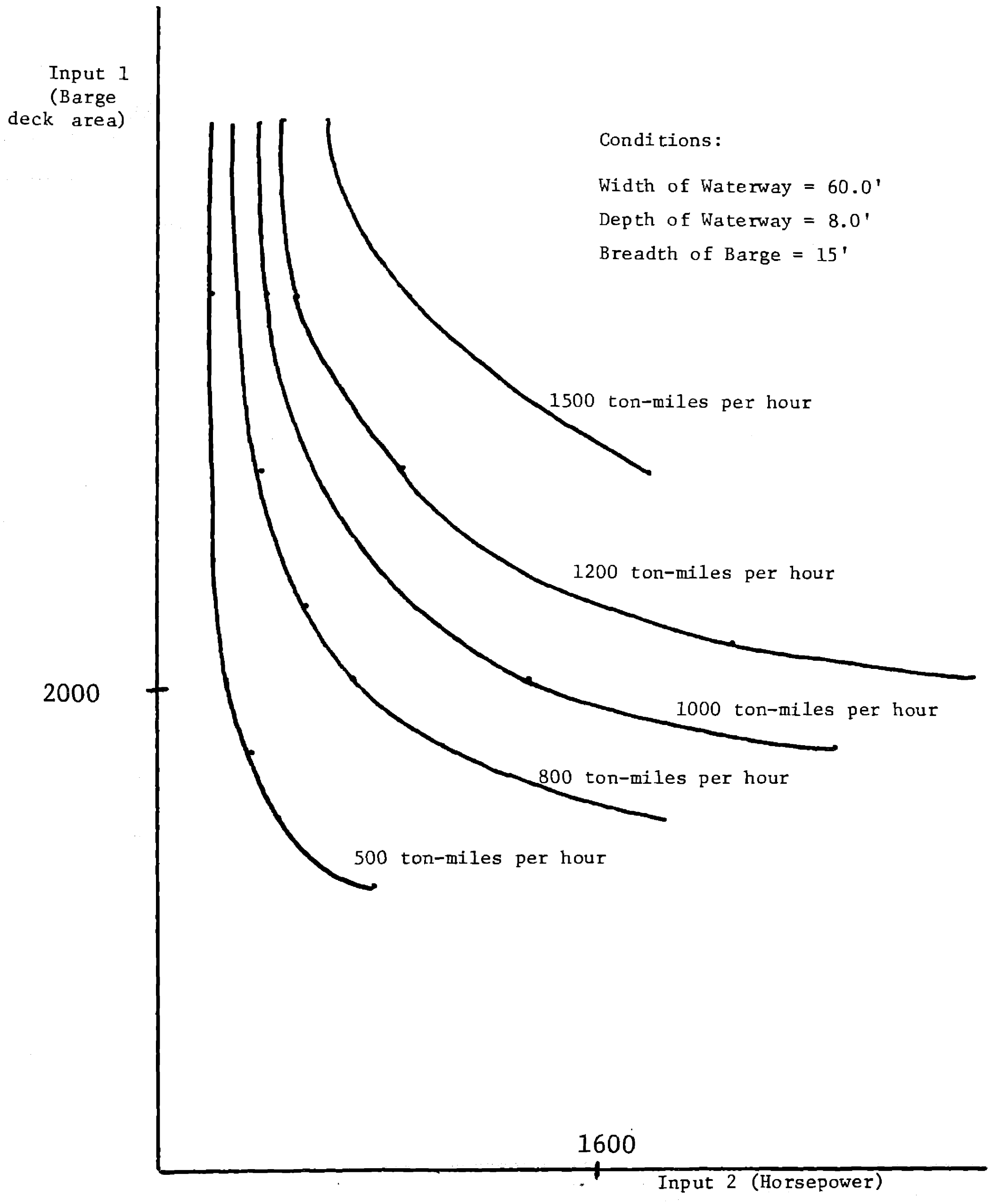


FIGURE 3.6 ISOQUANTS FOR WATER TRANSPORT FOR STATED CONDITIONS

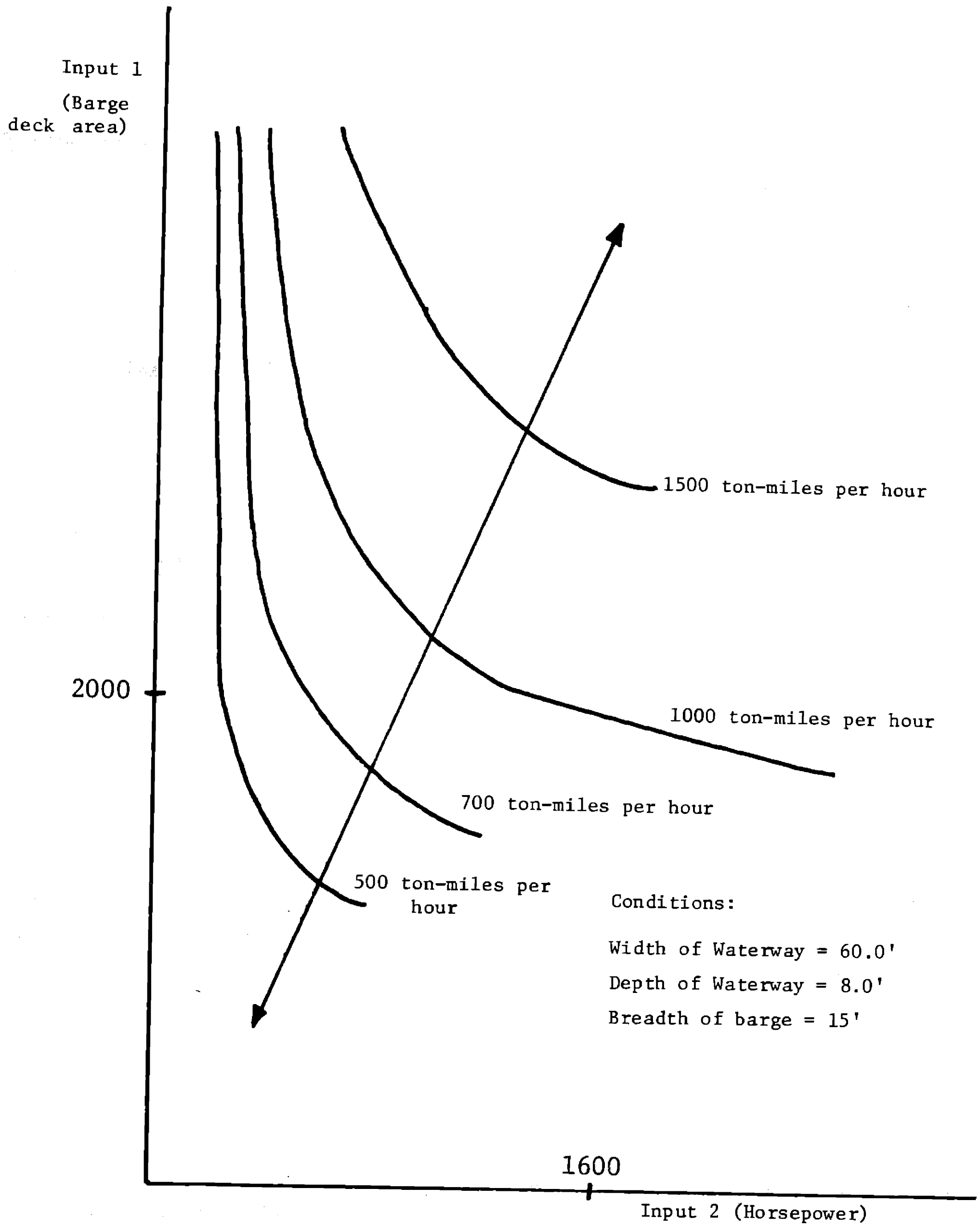


FIGURE 3.7 EXPANSION PATH FOR WATER TRANSPORT FOR STATED CONDITIONS

prevailing conditions (in this case that there is no current), the optimal ratio of the inputs to the production function will not change as the capital expenditure budget increases, i.e. as the isocost lines move further away from the origin. The production function is then linear and homogeneous.

3.6 Effect of Stream Current Velocity

As would be expected, the existence of stream currents of varying velocities proportionately increase or decrease the downstream or upstream barge flotilla velocities respectively (Figure 3.8). What is more significant is that the average velocity, both upstream and downstream, decreases non-linearly with increasing stream current velocity (Figure 3.9). This fact implies that the horsepower needed to maintain a constant average velocity, say S_c, over both upstream and downstream travel, must increase non-linearly and more than proportionately to the increase in stream current velocity (Figure 3.10).

From these facts it follows that the primary effect of the existence of a stream current is to distort the production function. This can be seen by comparing the total product curves for a stream current of 6 mph (Figure 3.11) with those

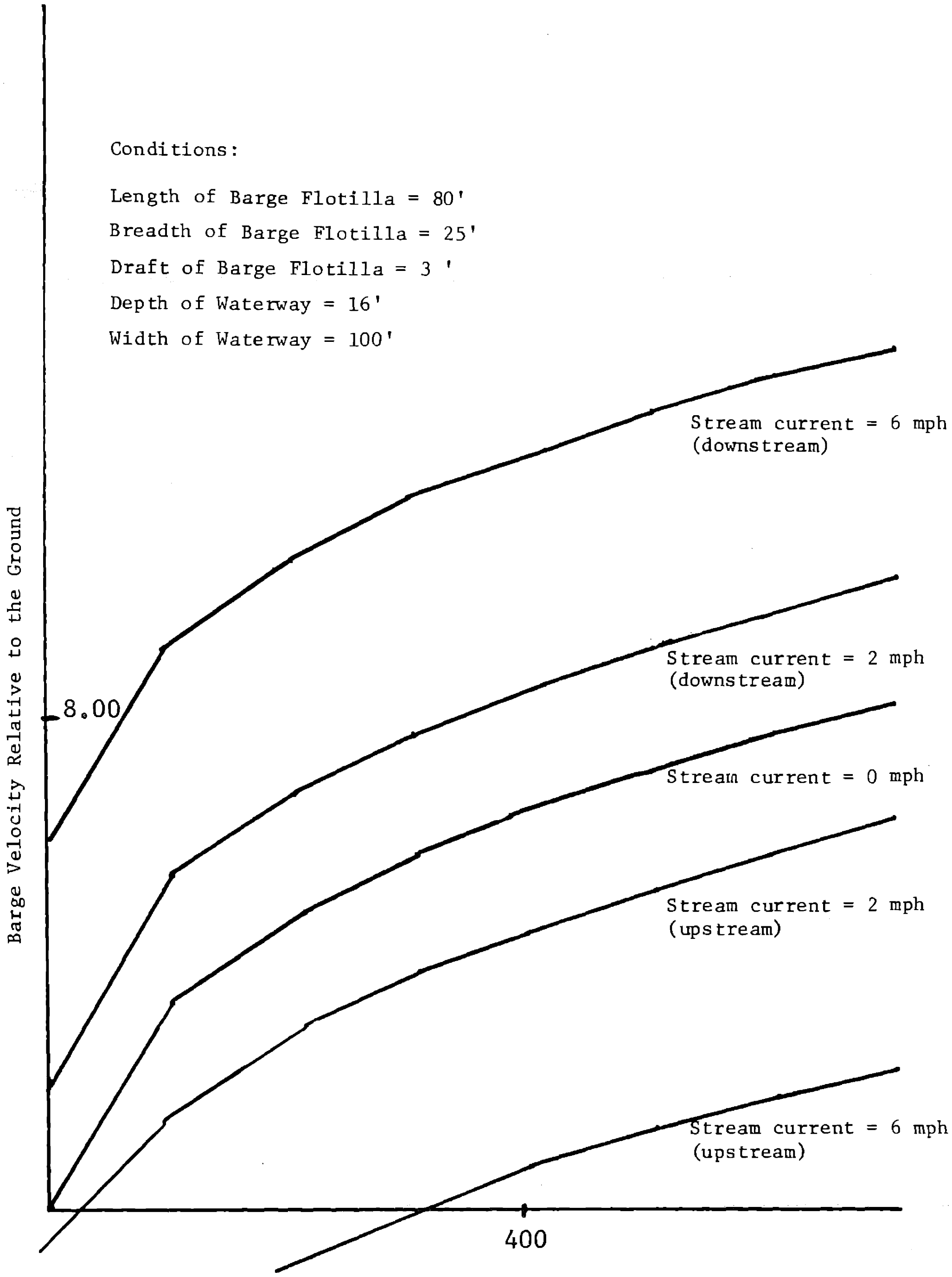


FIGURE 3.8 THE EFFECT OF A CURRENT IS TO LOWER AVERAGE ROUND TRIP SPEED AND OUTPUT

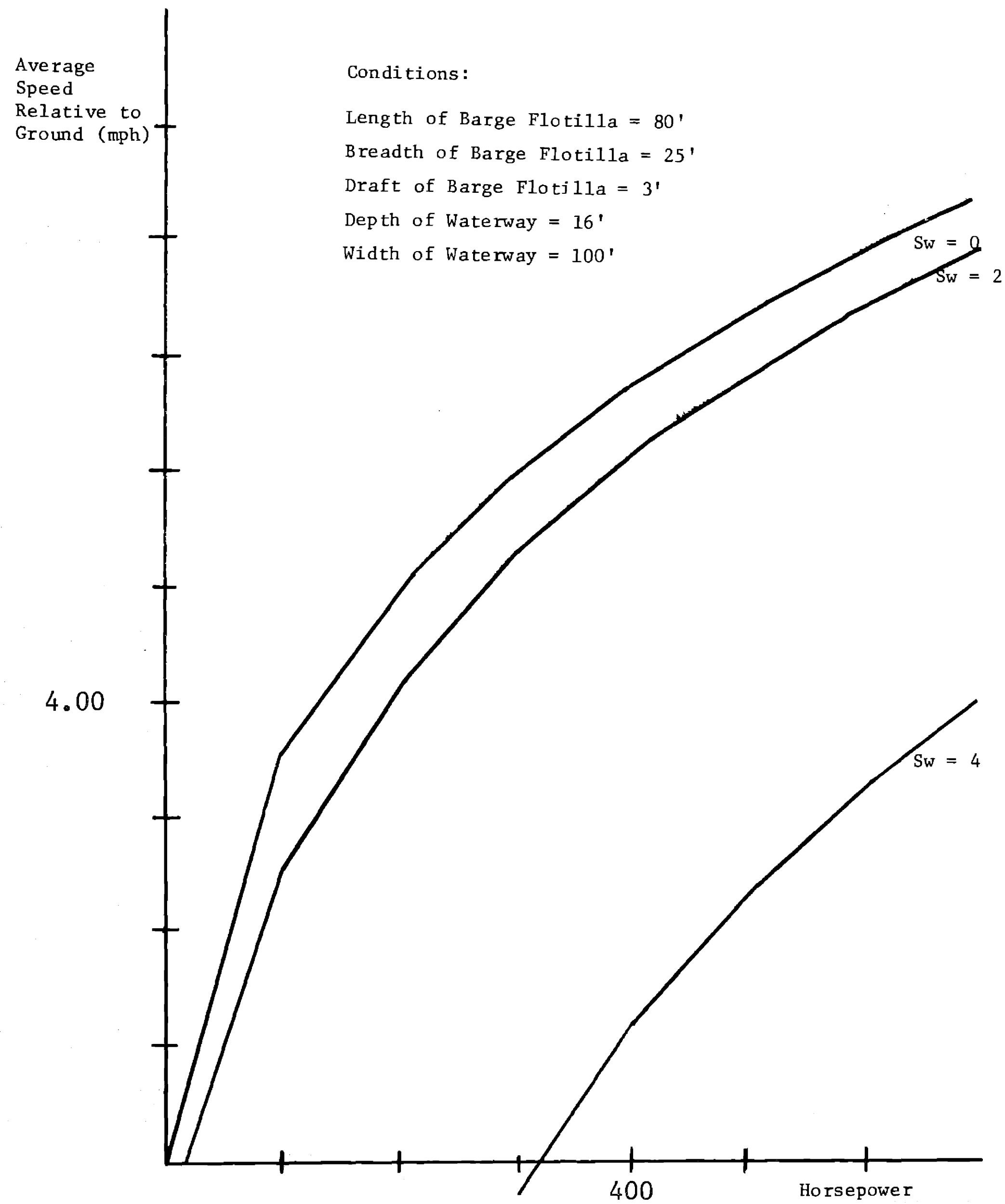


FIGURE 3.9 EFFECT OF CURRENT ON OUTPUT OF WATER TRANSPORT IS HIGHLY NON-LINEAR

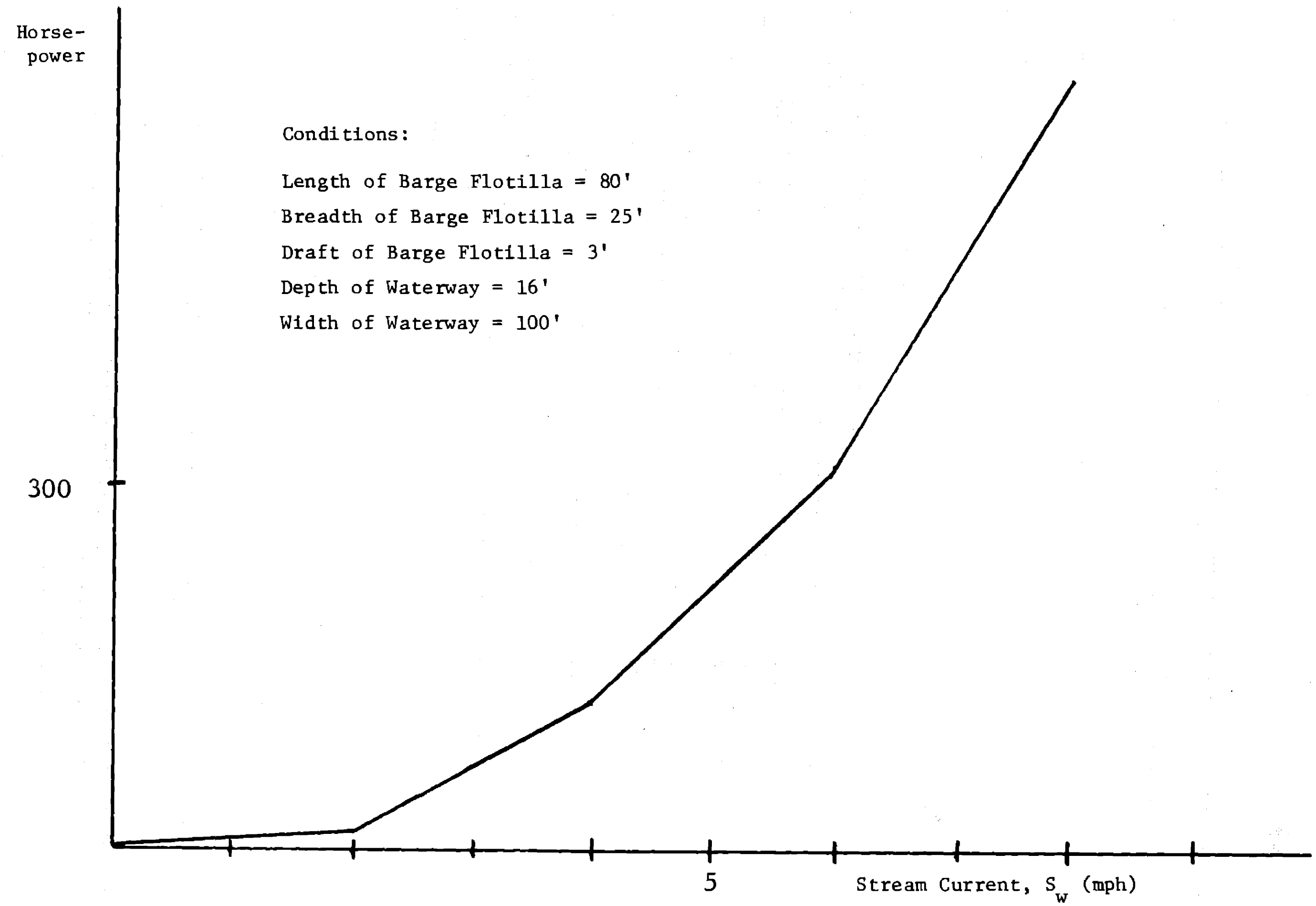


FIGURE 3.10 HORSEPOWER REQUIRED TO MAINTAIN CONSTANT OUTPUT OF WATER TRANSPORT INCREASES EXPONENTIALLY WITH CURRENT VELOCITY

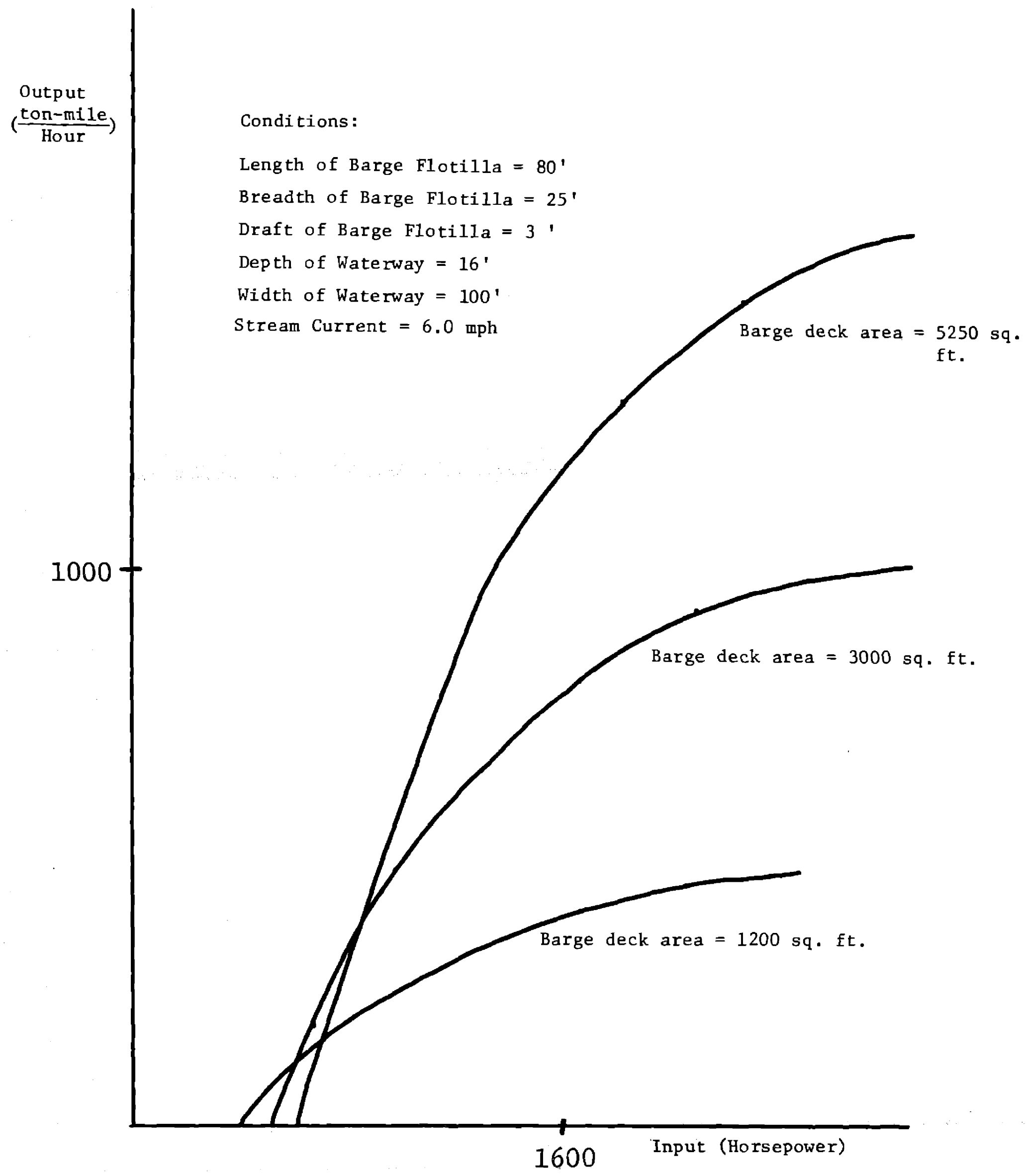


FIGURE 3.11 THE PRODUCTION FUNCTION IS DISTORTED AND THE TOTAL PRODUCT CURVES LOWERED BY STREAM CURRENT

for still water (Figure 3.5). The stream current also lowers the output levels due to a decreased average speed attained.

The distortion due to the existence of a stream current transforms the production function to a linear, non-homogeneous production function with a linear expansion path which, however, does not pass through the origin (Figure 3.12). This means that, given the prices of the inputs, the optimal ratio of the inputs to the production function will change as the capital expenditure budget increases, i.e., as the isocost lines move further away from the origin.

This is an important conclusion since, with the existence of a stream current, we can no longer work with one constant optimal ratio of inputs, but rather the optimal ratio will change with the amount of capital invested.

3.7 Effect of Maximum Barge Length Constraint

Due to various waterway constraints that the barge flotilla may encounter (e.g. bends in the river), a maximum length for the barge may have to be specified. Under these conditions, where increased barge deck area can only be achieved by increases in the breadth of the barges, the tow will be subject to increasing returns to scale up to a critical size. This critical size is a function of the channel width and depth, and the

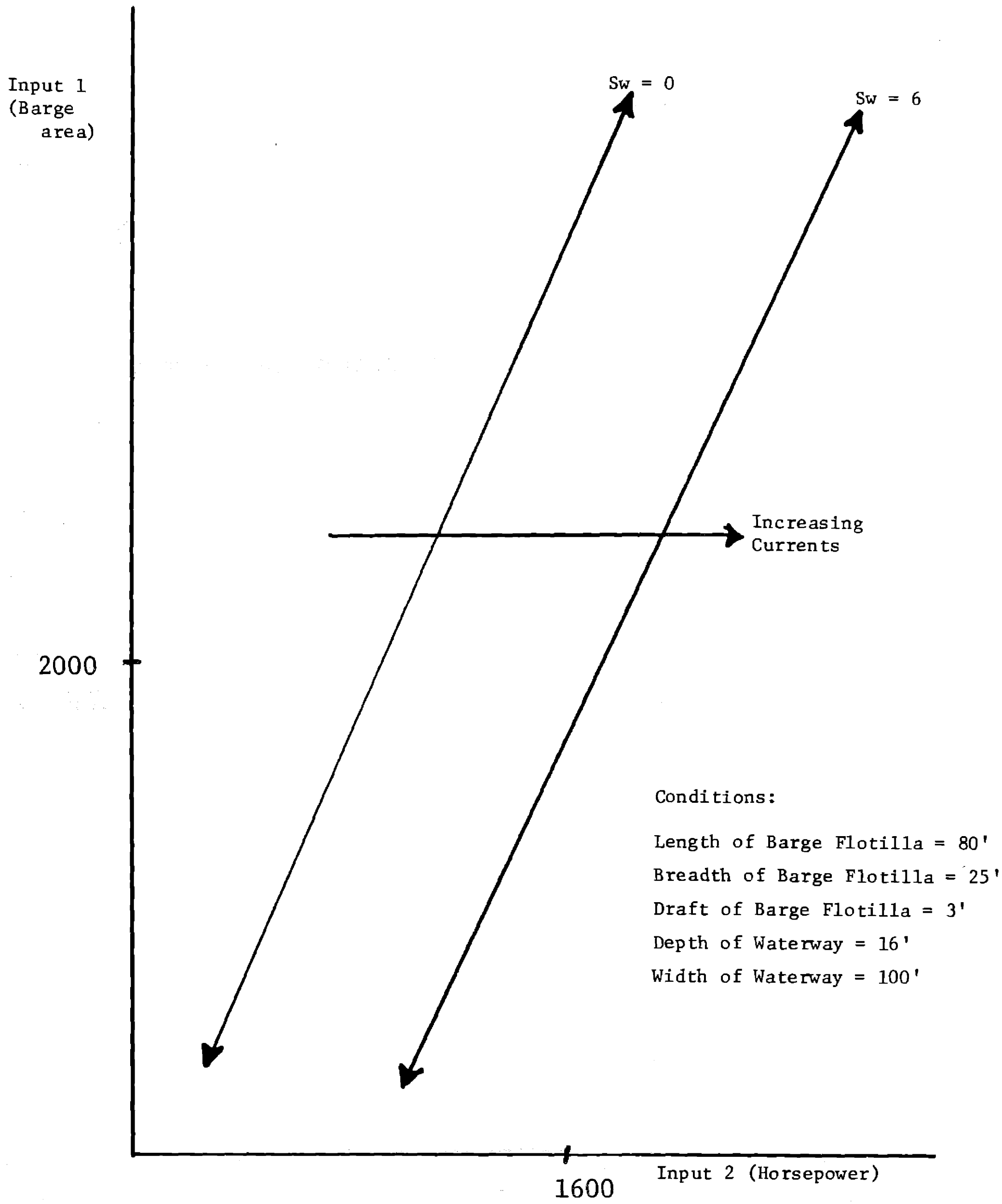


FIGURE 3.12 THE EXPANSION PATH AND THE OPTIMAL DESIGN FOR WATER TRANSPORT IS SHIFTED BY STREAM CURRENTS

maximum permissible barge flotilla length consistent with navigating in that river environment. Beyond this point, the tow is subject to decreasing returns to scale within a waterway of given depth and width (Figure 3.13). This result will always hold, for as flotilla breadth approaches channel width, or as flotilla draft approaches channel depth, resistance increases without bound. Further, as the horsepower increases relative to the unobstructed channel cross-section, effective push decreases because of restricted water flow to the propeller screws of the towboat. Also, the resistance of the barge flotilla increases because of an extreme drawing of water from under the flotilla, causing the barge to "squat."

On smaller waterways, the onset of decreasing returns would probably be a very real operating constraint.

The existence of a maximum barge length constraint will lead to the existence of dominated solutions as shown in Figure 3.14. By increasing the barge deck area solely through widening the barge, a maximum output in ton-miles per hour will be reached at a given deck area. Any further increases in barge deck area will actually result in lowered output. Thus the maximum barge length constraint leads to the existence of barge deck areas which maximize output.

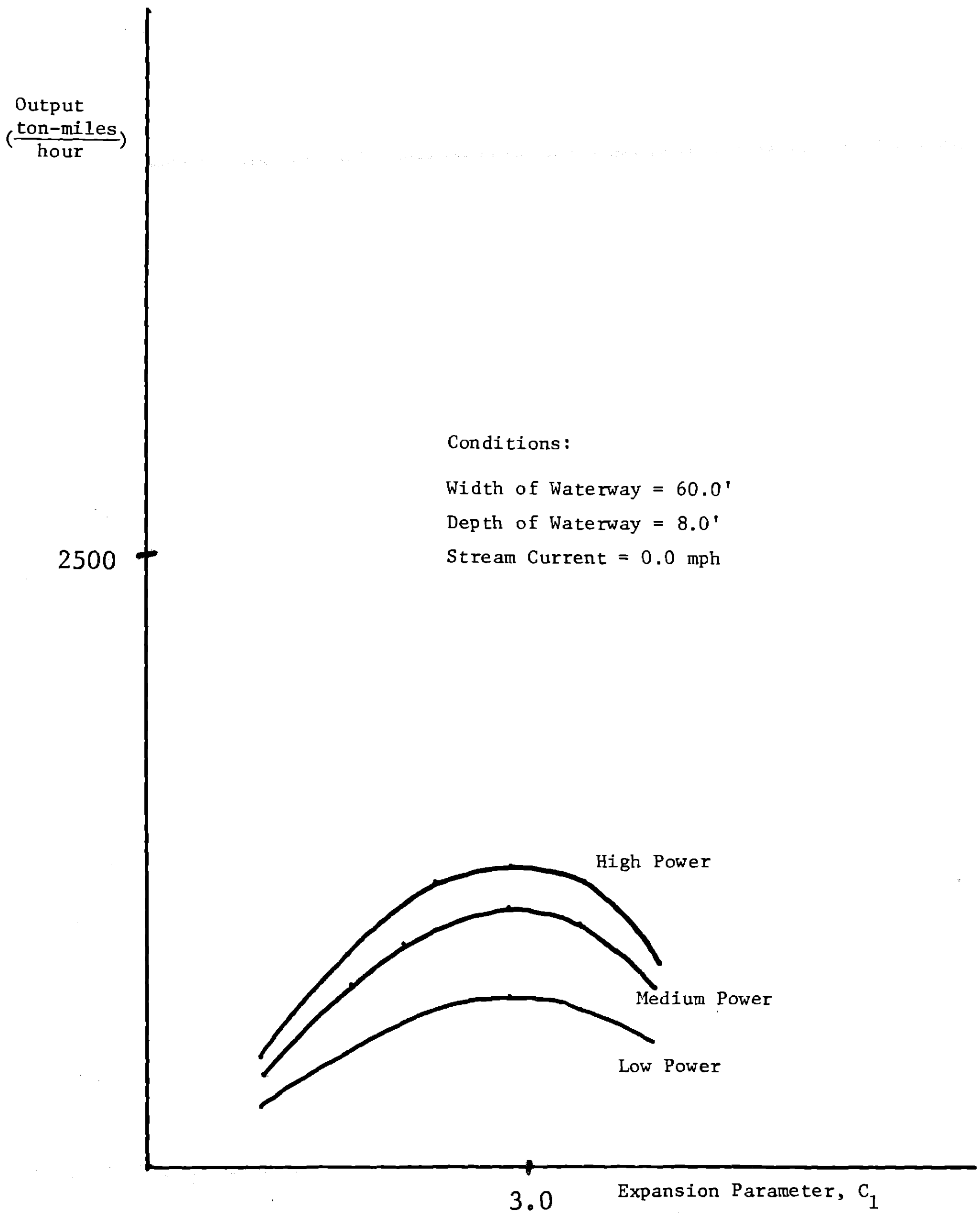


FIGURE 3.13 DECREASING RETURN TO SCALE EXIST FOR WATER TRANSPORT WHEN BARGE DIMENSIONS ARE CONSTRAINED

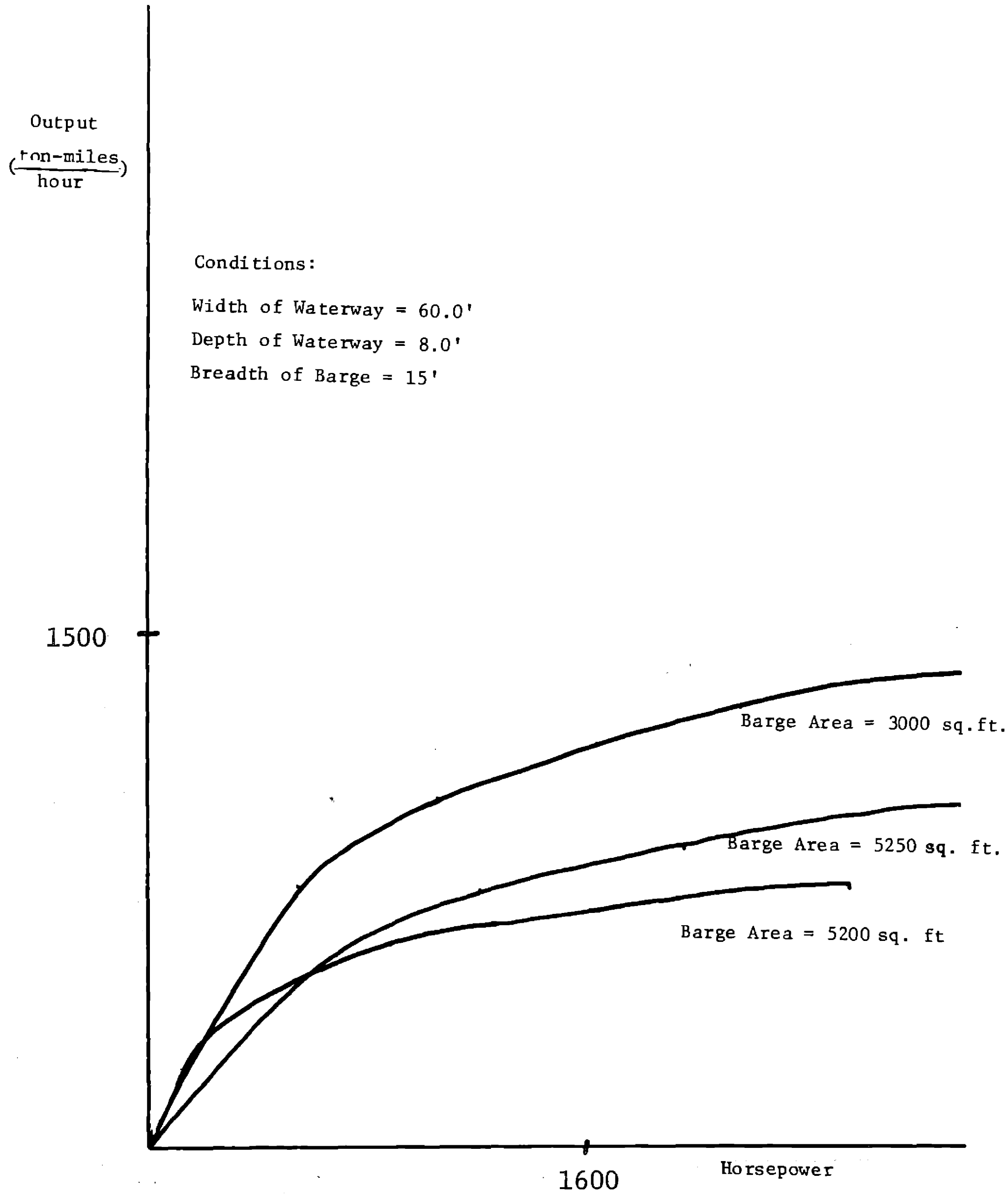


FIGURE 3.14 DOMINATED DESIGNS EXIST WHERE DESIGN DIMENSIONS ARE LIMITED

The existence of a maximum barge length constraint will also lead to a distortion of the production function and consequently a change in the expansion path. However, instead of the expansion path being translated to the right parallel to the original expansion path, with no stream current and no barge length limitation, the expansion path has been rotated to the right, that is, toward a higher horsepower to square feet ration (Figure 3.15).

This distortion due to the existence of a maximum barge length constraint has again transformed the production function into a linear, non-homogeneous function with a linear expansion path which does not pass through the origin. Thus, as with the existence of a stream current, the optimal ratio of the inputs to the production function will change as the capital expenditure budget increases.

3.8 Combined Effect of Stream Current Velocity and Maximum Barge Length Constraint

For river transport, there are generally both currents and length limitations. The combined effect of a stream current velocity equal to 6.0 mph and a maximum barge length constraint equal to 125 feet on the ton-miles per hour output measure gives

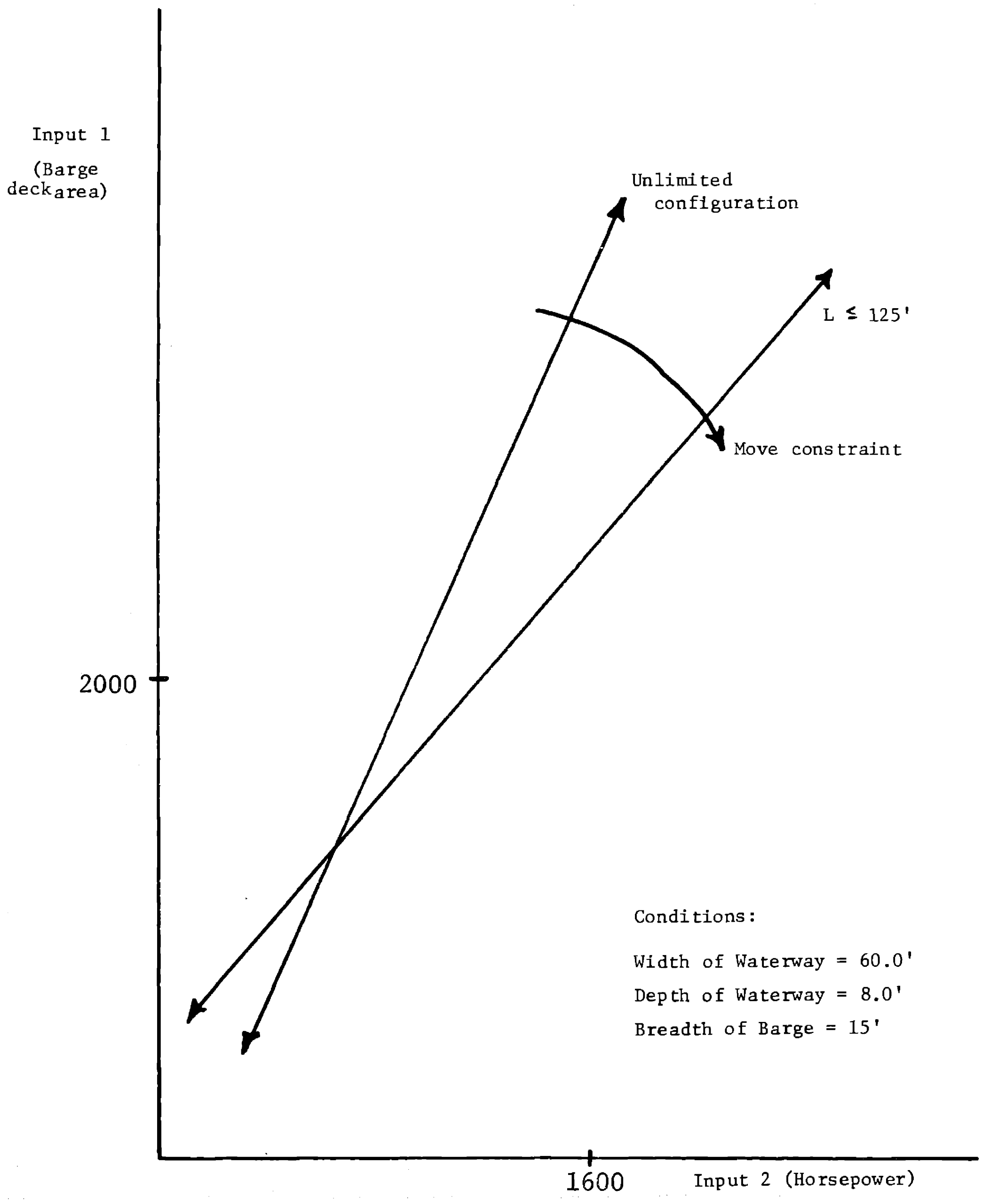


FIGURE 3.15 THE EXPANSION PATH AND THE OPTIMAL DESIGN FOR WATER TRANSPORT IS ROTATED BY LENGTH LIMITATIONS

rise to dominated solutions as we saw previously with only a maximum barge length constraint (Figure 3.16). This means that a maximum output in ton-miles per hour will be reached at a given deck area and any further increases in barge deck area will actually result in lowered output. Thus the existence of the stream current velocity and the maximum barge length constraint lead to barge deck areas which maximize output.

With the combination of a stream current and a maximum length for the barge flotilla, the expansion path will be both rotated and translated from what it was in Figure 3.7. For the particular case illustrated in Figure 3.17, the expansion path does appear to pass through the origin. Thus the optimal ratio of inputs to the production function will not change substantially as the capital expenditure budget increases.

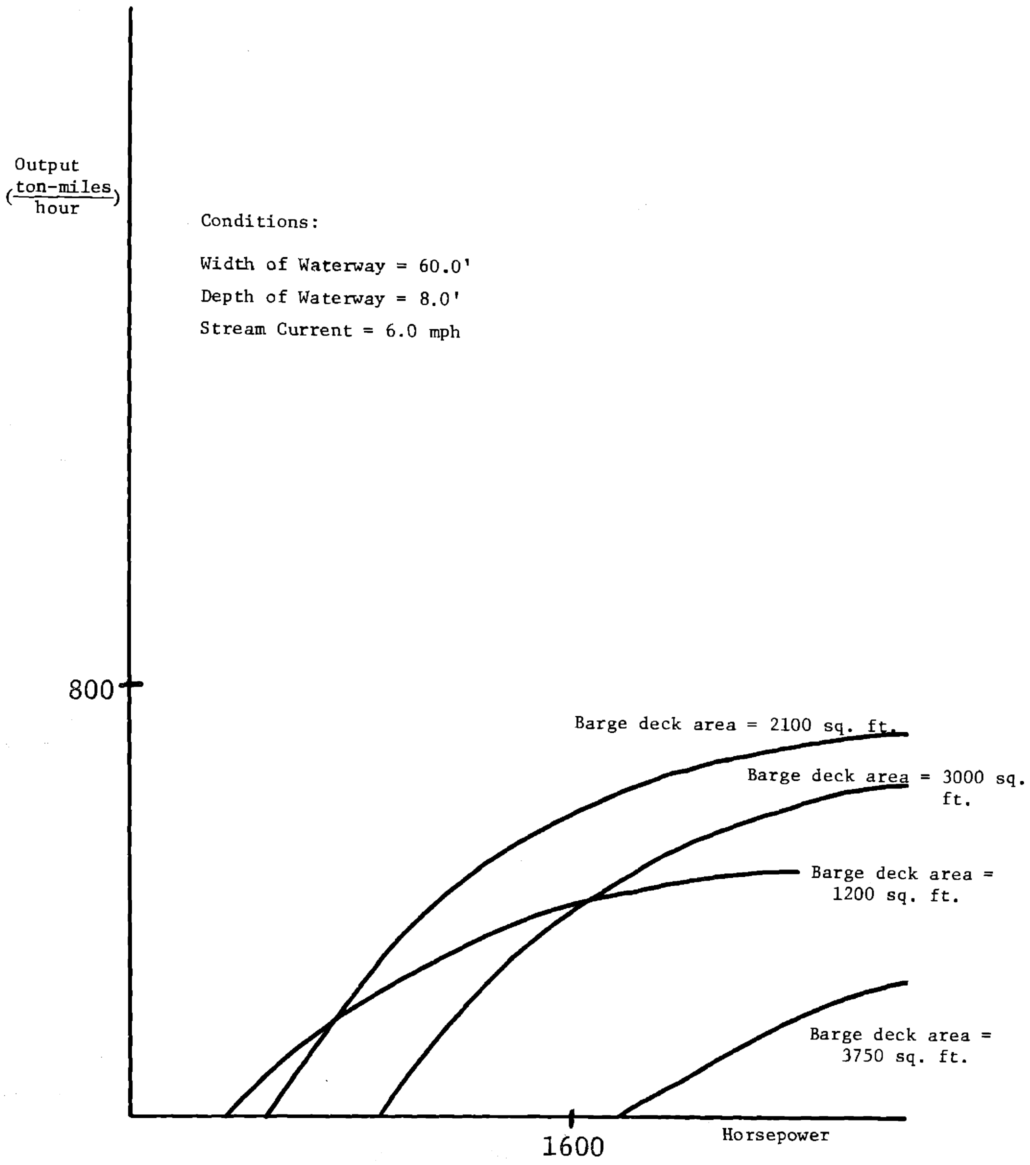


FIGURE 3.16 DOMINATED DESIGNS FOR COMBINATION OF BOTH CURRENTS AND LENGTH LIMITATIONS

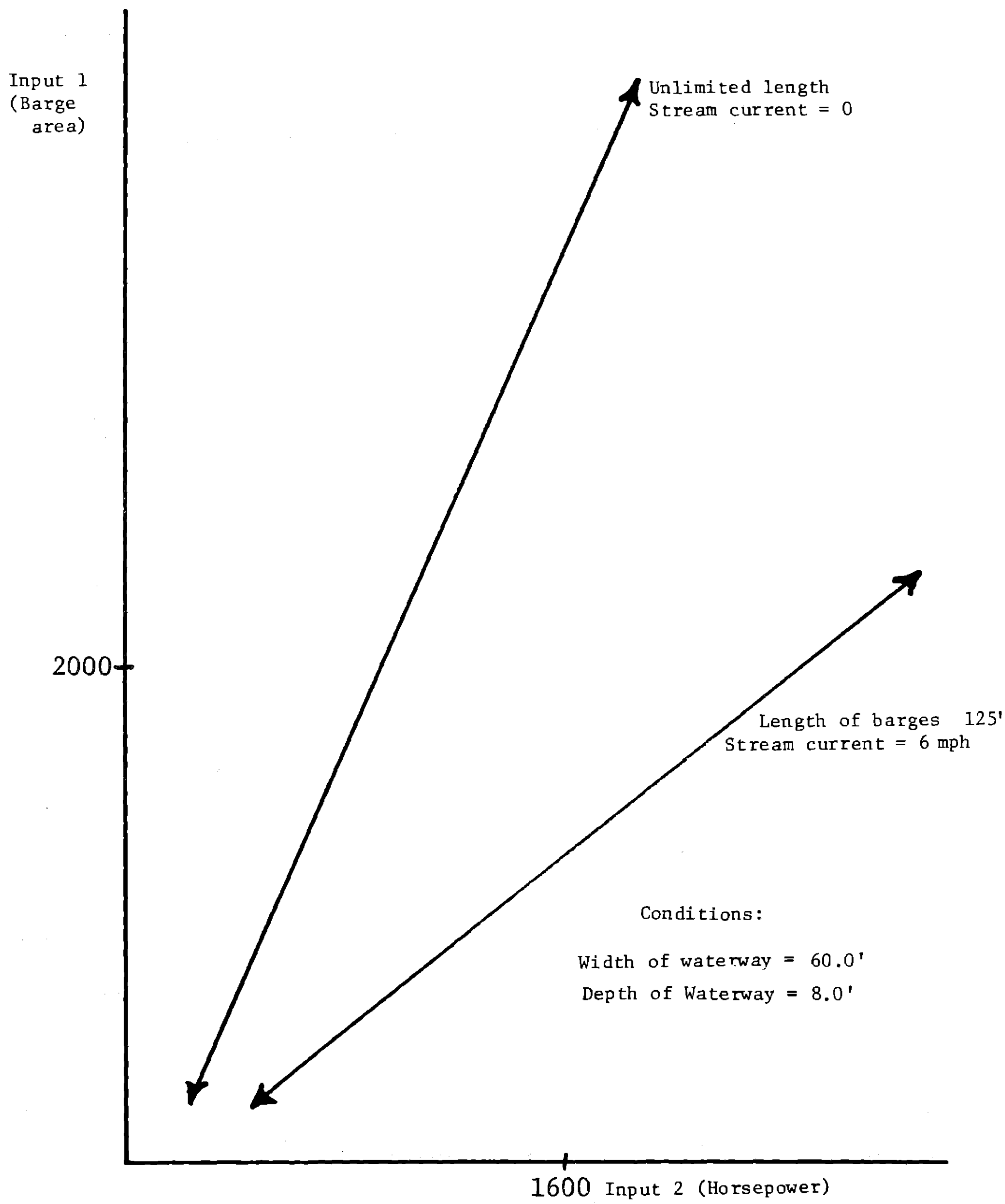


FIGURE 3.17 THE EXPANSION PATH FOR RIVER TRANSPORT MAY BE LOWER AND HOMOGENOUS

CHAPTER 4. SENSITIVITY ANALYSES

4.1 Varying Relative Cost Conditions

Since absolute costs of transportation are difficult to determine in advance, and are, in any case, likely to fluctuate, it is desirable to use a cost estimation procedure which defers the introduction into the analysis of specific costs for as long as possible. Fortunately, this is most possible when using an engineering production function.

The use of relative costs leads to a more precise picture of what designs are optimal. Such relative values, as for example, that the cost of one horsepower of engine is approximately equal to two square feet of barge construction are easier to obtain and allow one to test the sensitivity of the expansion path location to changes in costs.

Figure 4.1, which shows the change in location of the expansion path as relative costs change, confirms the fact that we are dealing with a linear homogeneous expansion path since the approximated expansion paths pass through the origin and are linear. As would be expected, as barge deck area becomes less expensive relative to horsepower, the related expansion path

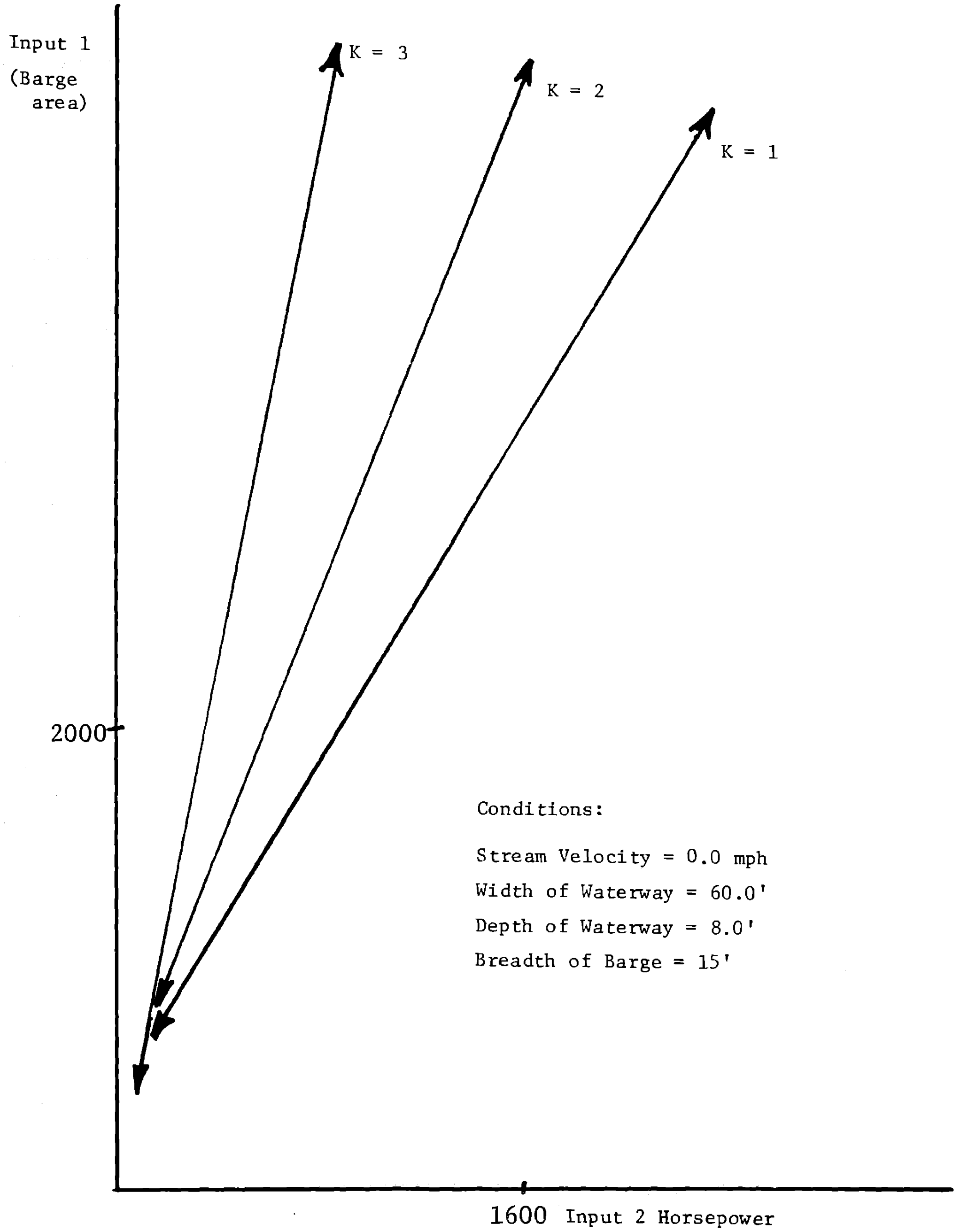


FIGURE 4.1 EXPANSION PATHS FOR VARYING RATIOS OF INPUT PRICES (PRICE HORSEPOWER = K PRICE SQUARE FOOT OF BARGE AREA) FOR STATED CONDITIONS

moves closer to the vertical axis.

These ratios of relative costs can reflect the fact that horsepower is a capital-intensive and technology-intensive input while barge deck area construction is generally more labor-intensive. The relative cost ratios used may reflect the fact that skilled or unskilled labor, used in barge construction, is generally more abundant and cheaper in developing countries. Also, higher horsepower to barge deck area relative costs may reflect the fact that, in developing countries, technology-intensive items, such as diesel motors, must generally be purchased abroad, requiring foreign exchange which often has a high shadow price.

Figure 4.2 shows the same sensitivity analysis when there now exists a 6.0 mph stream current. Again, we note that the existence of a stream current translates the expansion paths parallel and toward increased horsepower. In this case, note that the optimal ratio of the inputs to the production function will depend upon the stream current velocity and the cost ratio of the inputs.

When there exists a maximum barge length constraint but no stream current (Figure 4.3) the effect is one of rotation of the expansion paths toward increased horsepower as noted before.

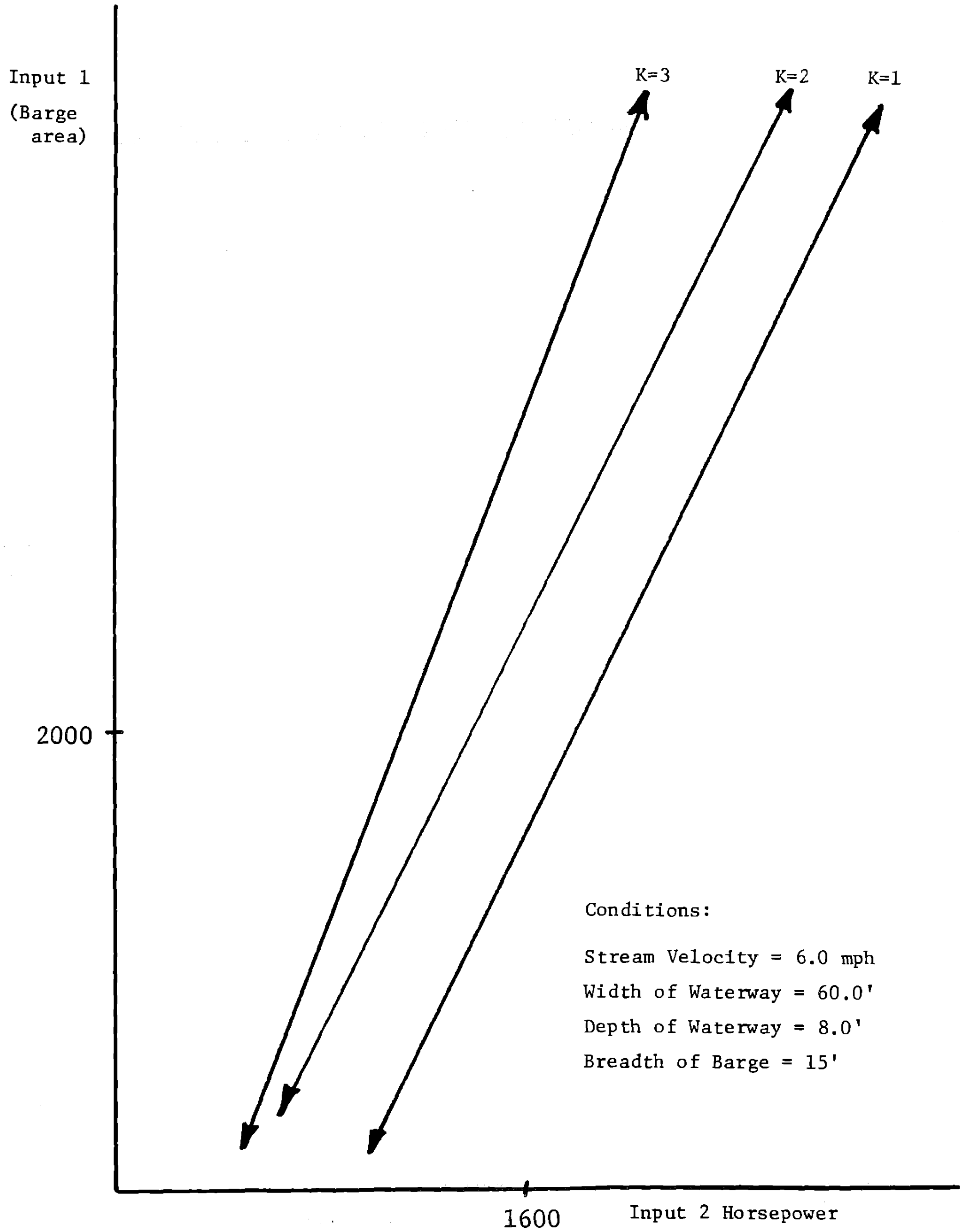


FIGURE 4.2 EXPANSION PATHS FOR VARYING RATIOS OF INPUT PRICES (PRICE HORSEPOWER = K PRICE SQUARE FOOT OF BARGE AREA) FOR STATED CONDITIONS

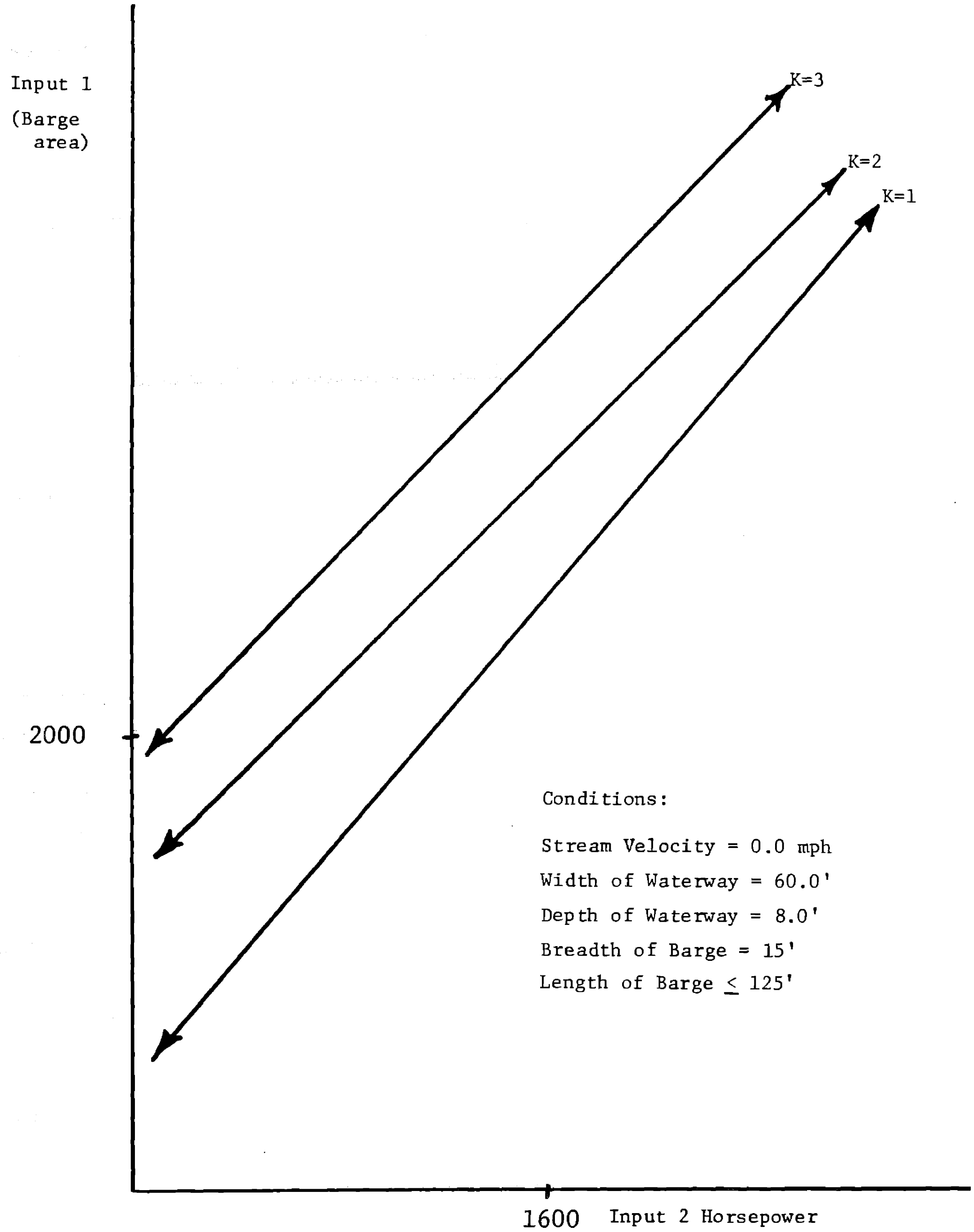


FIGURE 4.3 EXPANSION PATHS FOR VARYING RATIOS OF INPUT PRICES (PRICE HORSEPOWER = K PRICE SQUARE FOOT OF BARGE AREA) FOR STATED CONDITIONS

Finally, when there exists both a stream current and a maximum barge length constraint, the effect, as noted before, is one of combined translation and rotation,as shown in Figure 4.4.

4.2 Speed versus Cost Tradeoffs

Tradeoffs between increased level of service, as defined by speed, and cost can be generated explicitly using the model and the previous results. An example is shown in Figure 4.5, which illustrates that, for a given barge deck area, there is a value of horsepower which yields a minimum cost per ton-mile per hour. One can also see that deviations from this minimum in the direction of increased horsepower are less costly in terms of cost divided by output productivity than are deviations in the direction of less horsepower. There may thus be a positive benefit to designing water transport with higher horsepower, especially when the goods being transported are perishable.

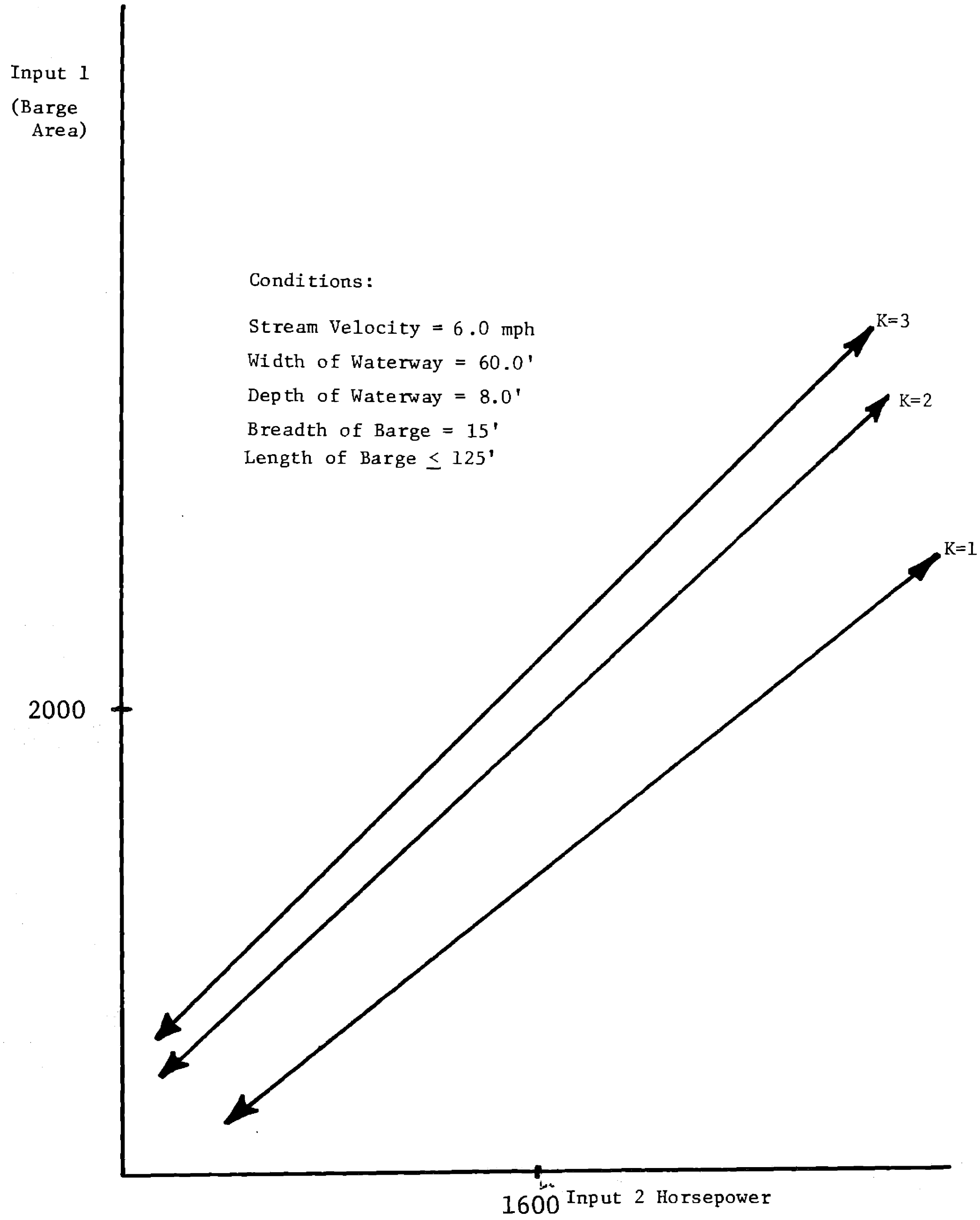


FIGURE 4.4 EXPANSION PATHS FOR VARYING RATIOS OF INPUT PRICES (PRICE HORSEPOWER = K PRICE SQUARE FOOT OF BARGE AREA) FOR STATED CONDITIONS

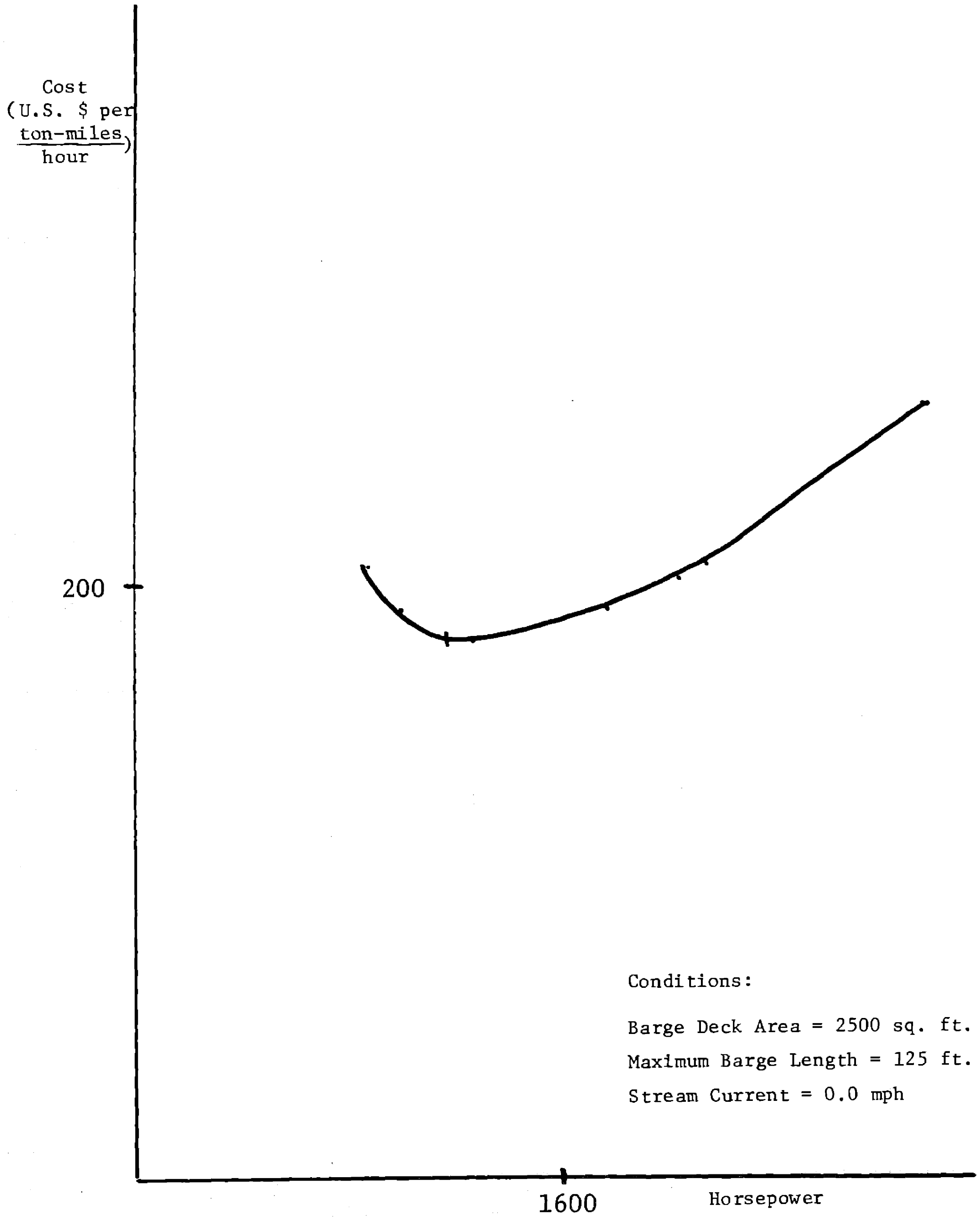


FIGURE 4.5 TRADEOFFS BETWEEN LEAST COST OF TRANSPORT AND HORSEPOWER AND THUS SPEED

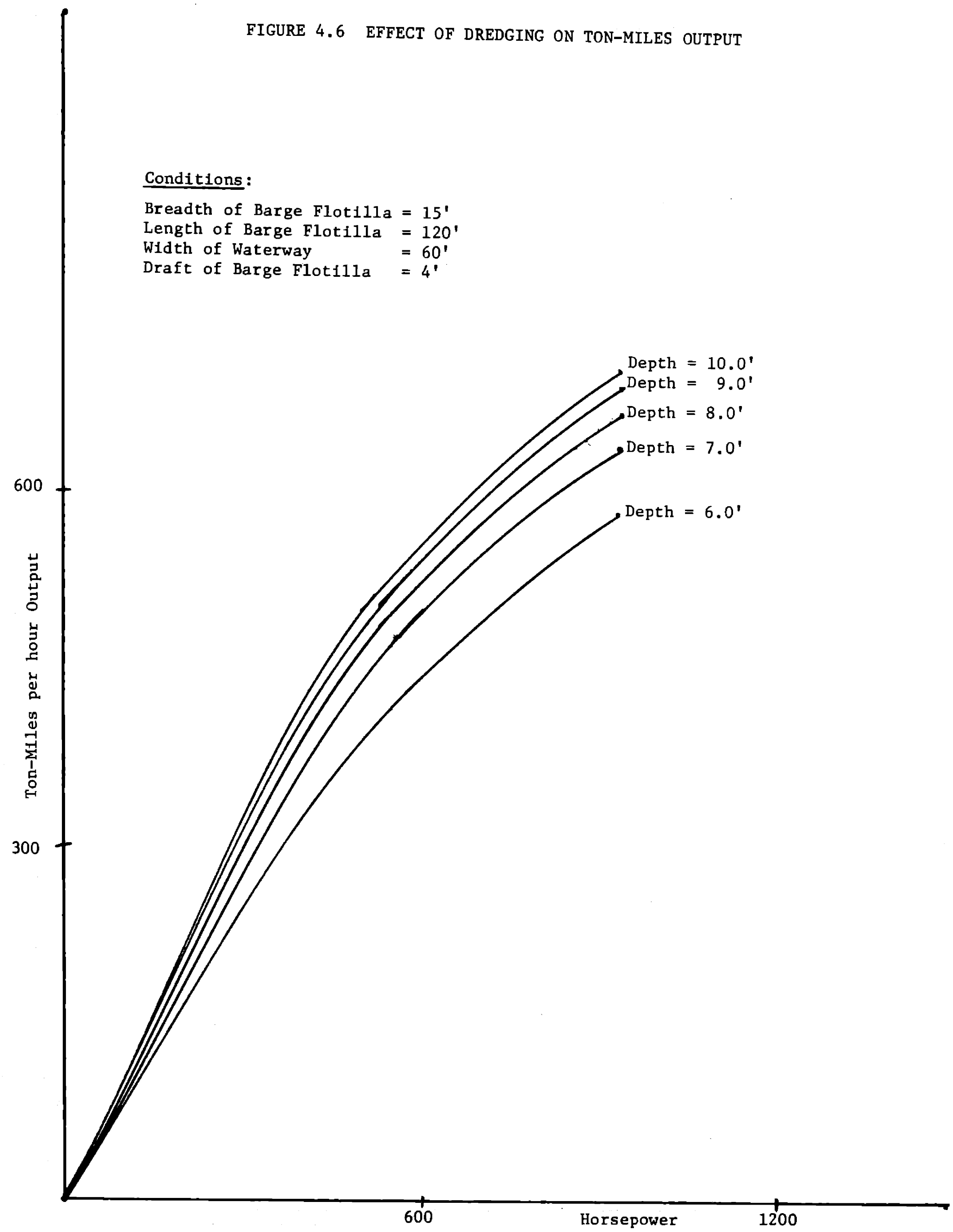
4.3 Tradeoffs between Dredging and Increased Horsepower of the Towboat

4.3.1 General Discussion

As is shown in Figures 4.6 and 4.7, for equal effectiveness, definite tradeoffs exist between dredging the given waterway and increasing the horsepower of the towboats which operate on the waterway. Dredging, in the usual case, is a public sector expense, while increasing the horsepower of the towboats is a private sector expense, accruing to the individual bargeline firm. As regards expenditures, therefore, these tradeoffs occur between the public sector and the private sector of the economy. In another sense, one is trading off investment in the waterway environment versus investment in the individual bargeline firm's equipment.

One can generate the technical tradeoff curves such as in Figure 4.6, but when deriving the relative or absolute costs of these tradeoffs, one must know, in the specific situation being considered, the length and breadth of the river or waterway which is to be dredged and what is the cost of increased horsepower to the bargeline firm. When discussing cost tradeoffs between dredging and more powerful towboats, one must know the cross-

FIGURE 4.6 EFFECT OF DREDGING ON TON-MILES OUTPUT



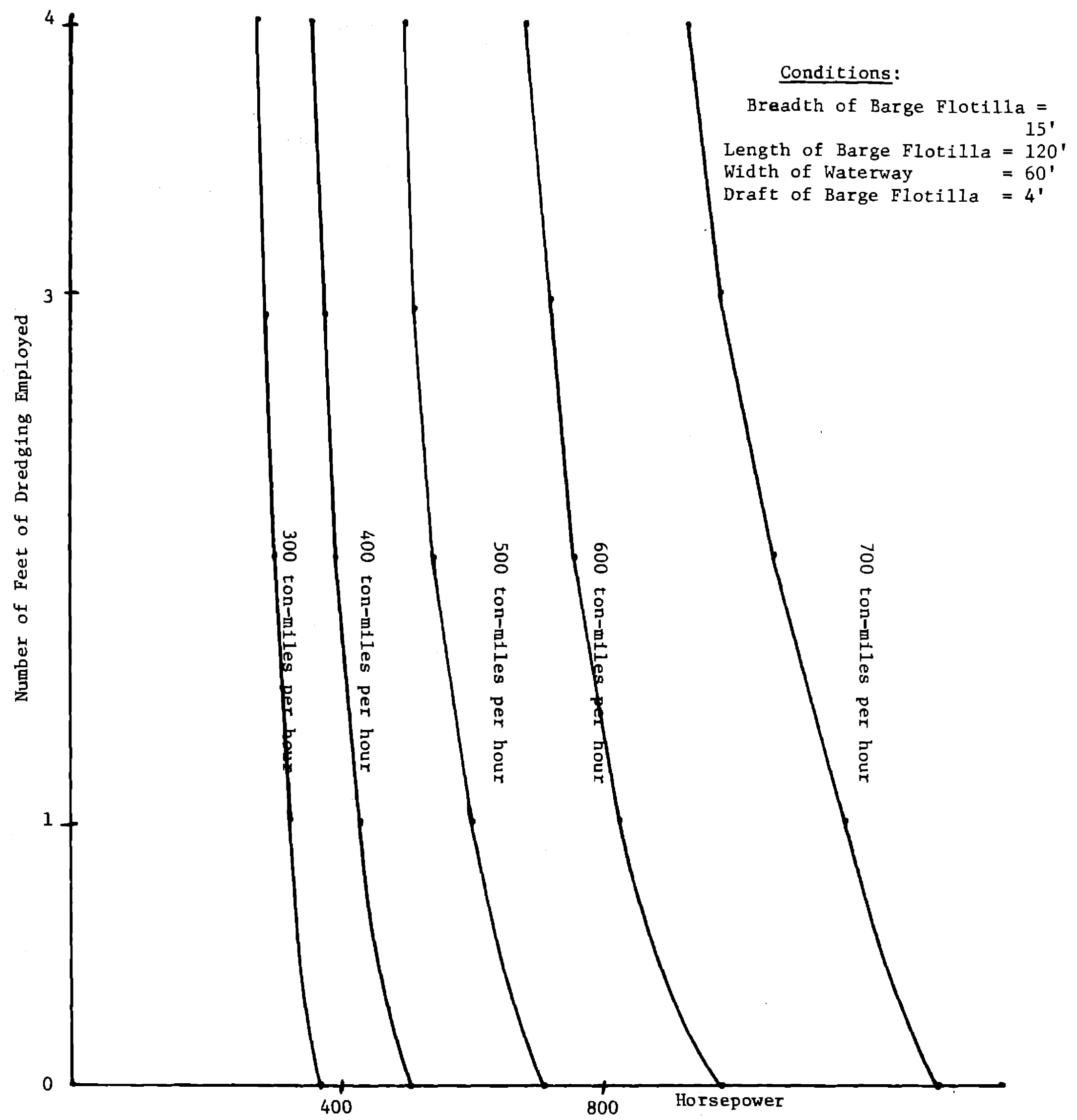
section of the navigable channel and the length to be dredged, as well as the depth of dredging.

Let us first restrict our attention to the technical tradeoffs shown in the form of isoquants in Figure 4.7. These isoquants have been derived in the usual manner from Figure 4.6, and contain only the information inherent in the production function itself. They contain no information regarding relative costs of dredging or increased horsepower. Firstly, one can see that the tradeoffs are very small (i.e., the isoquants remain quite steep) until higher output levels are reached. This implies that dredging should be used only for more congested waterways where the volume of movement of goods and relative size of the barge flotilla are large. Secondly, the shape of the curves imply that, for the conditions shown, dredging to greater and greater depths brings diminishing marginal returns.

4.3.2 Cost Tradeoff Example

As a specific example of the cost tradeoffs which can be made between investments in dredging and investments in more powerful towboats, let us refer to Figure 4.6. At 560 horsepower, by dredging from a depth of 6 feet to a depth of 7 feet, one can increase the ton-miles per hour output from 425 to 480. Since,

FIGURE 4.7 TRADEOFFS BETWEEN DREDGING AND INCREASED HORSEPOWER EXIST FOR EQUAL EFFECTIVENESS DESIGNS



for the barge conditions given, 101.5 tons is being carried, the speed of the flotilla at the greater depth is:

$$\frac{\text{480 ton-miles per hour}}{\text{101.5 tons carried}} = 4.72 \text{ mph}$$

while it is $\frac{425}{101.5} = 4.19$ mph at the lesser depth.

In effect, the dredging, by increasing the cross-section of the stream, increases the speed of the towboat flotilla.

If we put our results on a per unit basis, i.e. if we dredge a depth of 1 foot for one mile, over a 60 feet width of the river, this will mean dredging

$$(1 \text{ foot}) \times (5260 \text{ feet/mile}) \times (1 \text{ mile}) \times (60 \text{ feet}) = 315{,}600 \text{ feet}^3 \text{ or } 9050 \text{ meters}^3.$$

At a unit price of dredging in the Magdalena River in Colombia, South America of 10 pesos/cubic meter (1) reflecting the prevailing labor wage rates in Colombia, this amount of dredging would cost about 90,500 pesos or about U.S. $4,520 per mile, reflecting an exchange rate of 20 pesos/dollars.

On the other hand, to increase output from 425 ton-miles per hour to 480 ton-miles per hour would require an increase in horsepower from 560 horsepower to 675 horsepower. At a cost of approximately U.S. $55 per horsepower (3) this increase in horsepower would cost:

(675-560) x \$55 = \$6,325

This expense would, of course, be useful no matter how many miles were to be travelled, and would certainly entail benefits even as regards increased speed - even where dredging were not done.

In any specific situation requiring dredging, one would have to evaluate the cost of the dredging for the distance specified. The example is only demonstrative of the manner in which cost tradeoffs could be made. The relative cost advantage would shift for different total distances to be dredged.

The example also shows that the two inputs we are trading off are not really equivalent in their effectiveness. The cost of dredging represents only the cost for one mile's cruising distance, whereas the horsepower expenditure buys the increase in output over all distances travelled.

4.3.3 Conclusions

In summary, the following conclusions emerge from the considerations of the technical and cost tradeoffs involved with dredging:

1. In Figure 4.7, one can see that the tradeoffs are very small (i.e., the isoquants remain quite steep), until higher

output levels are reached. This implies that dredging should be used only for more congested waterways where the volume of movement of goods and relative size of the barge flotilla are large.

2. The shape of the isoquant curves implies that dredging to greater and greater depths brings diminishing marginal returns.

3. The cost tradeoff example shows that dredging is highly expensive; and therefore it is cost-effective for short distances, for considerable traffic, or where we are talking about dredging a new canal, where extensive cost savings can be effected (such as a canal between two rivers).

CHAPTER 5. PLANNING FUNCTION CONSIDERATIONS AS A LOGICAL EXTENSION TO THE PRODUCTION FUNCTION

By dealing, up to now, with the production function, we have been treating the inland waterway transport problem from the supply side only, and abstracting from demand considerations. However, in the inland waterway industry, a firm must manage the boats and barges it owns or leases in such a way as to accommodate the demands of its customers. Primarily, a firm operates its equipment on only one river or waterway. The problem of optimal equipment selection would be much more complex if a firm operated on several waterways of differing characteristics - i.e., channel dimensions, currents, number of locks, and degrees of congestion. However, by operating on only one particular river, and if the origins, destinations, and timing of cargo permitted, the firm could presumably select a uniform tow size that would minimize the average cost of transport per ton-mile on its particular waterway. In line with the discussion of Returns to Scale to the

Production Function in Section 3.3, this optimum size of tow would become larger with increasing size and decreasing congestion of the waterway on which it operates. That is to say, the phenomonen of increasing returns to scale would be quite prominent (8).

As shown in Chapter 6, many operating tows fall below that optimum size because of the variety of origin-destination pairs and availability of cargo, although some tows may be made larger for scheduling reasons. This observation must lead us to distinguish between Returns to Scale for the barge-towboat flotilla (treated in Section 3.3), and returns to scale for the entire bargeline firm. The following statements provide a link between returns to scale for the tow and overall returns to scale for the bargeline firm:

1. The barge-towboat flotilla must exhibit decreasing returns to scale beyond some size in a particular environment;
2. The larger and less constricted the waterway, the larger will be this critical tow size;
3. For normally prevailing origin-destination demand patterns, the larger the critical tow size, the larger will be the percentage of a firm's tows

operating in the size range below critical size (6).

It must be remembered that the production function is a *technological* relationship *only* between inputs and output, subsuming only the elimination of technologically inefficient combinations of these inputs. This fact obviously raises difficulties in measuring inputs, especially the capital inputs.

The transportation industries in general, and the inland waterway transport industry in particular, make use of separable capital goods, for which the rate of output at any instant of time is directly related to that part of the capital stock currently in use. The idle part of the capital stock is completely irrelevant to the actual production process (though it may be quite relevant to other aspects of the firm's planning, such as meeting peak loads and improving the firm's competitive position vis-a-vis other carriers). Given the capital goods in use, changing the size of the total capital stock would in no way affect the rate of output. When working with data from actual waterway operations, these data do not represent observations on a production process at only one point in time, but rather the cumulative results over a finite time interval. During any such interval, variations in output rate occur with some corresponding variations in the utilization of towboats and barges.

It would not be adequate to measure the towboat or barge utilization simply by counting the number of units that were utilized at some time during the period, for some may have been used continuously while others may have been used for lesser amounts of time. Thus, for the purpose of comparing production function output from the model with actual logbook operating data, since, in reality, we are dealing with a production function for the case of separable capital goods, it would seem more appropriate to measure capital inputs as flows of services rather than as stocks; e.g. barge deck area-hours instead of barge deck area, horsepower-hours rather than horsepower of the towboat, etc. It would be necessary to have measures of the total utilization of the boat and barge stocks (6). Unfortunately, the data from the logbooks does not exist in this form, and a comparison of predicted and actual results was made in the preceding chapter using stocks of towboats and barges as inputs to the production function rather than flows of capital.

This preceding distinction seems valid when we stick to the concept of a production function as a technological relationship between inputs and output. However, due to conditions of fluctuating and uncertain demand for their services, unanticipated demands, and unusual destinations, individual firms do face decisions regarding the optimal stocks of capital equipment to be kept on hand. Thus it appears entirely possible that economies or diseconomies of scale may be present in the production function itself (with capital services as inputs), while additional but quite independent economies or diseconomies may obtain to the capital stock of the firm which it must hold in order to adapt optimally to a fluctuating and uncertain demand. To make a decision regarding the optimal stock of barges and towboats will involve the production function, but it will require also much more than just this technological relationship. For example, the strategy the firm adopts for handling peak demands, the availability of equipment on short-term rental, and the time-variability of demand will affect the stock-output relationship. It will involve all of the variables which must be considered in dynamic long-run profit maximization (8).

For an inland waterway transport firm, a larger volume of cargo may permit a higher proportion of larger, more efficient tows, and thus that firm may experience increasing returns to scale in the production function itself. However, the firm may experience increasing complexities in scheduling its equipment, and thus the stock of equipment might be increased more than in proportion to the increase in the rate of output.

Ultimately, this capital stock-output relationship and its scale economies or diseconomies will determine the firm's ability to expand line-haul operations without incurring increasing inefficiency. Such a relationship has been given the name of "planning function" to distinguish it from the purely technological production function (6).

The planning function (if it could be estimated statistically) could be compared with the explicit, quantitative production function and could give some indication as to how efficiently the firm can schedule its stock of towboats and barges and how efficiently the firm had adapted to fluctuating demand as the volume of output grew. For ultimately, this capital stock-output relationship will determine the firm's ability to expand line-haul operations without incurring increasing inefficiency.

An estimation of the planning function for separate firms could also give insight into the structure of the inland waterway transport industry (i.e., the size distribution of firms) or the effects of mergers on efficiency. Charles Howe and others have attempted to statistically estimate planning functions for individual bargeline firms (6).

CHAPTER 6. COMPARISON OF PRODUCTION FUNCTION MODEL WITH ACTUAL OPERATIONS

6.1 Introduction

In this chapter various sets of data gathered from towboat logbooks have been used, in conjunction with results obtained from the production function model, to determine whether actual operating conditions approximate optimality as defined with the production function model. If they do not, the reasons for deviation from the model's predicted results are explored.

For this purpose, three sets of logbook operating data as reported in Howe (7) were used. As discussed in Chapter 5, these data represent observations on the stocks of capital in use, and, as such, do not report rates of utilization of the capital stock, which would permit the use of capital flows as inputs to the production function. However, they do show the design characteristics of the barge and towboats in use on a particular waterway over a certain period of time.

It is to be emphasized that, in this chapter, we are exploring the conformity of actual operating data to optimal design conditions as predicted by the production model, using the data configurations as inputs. We are not attempting to use the operating data to verify the correctness of the model per se. To a great extent, the latter has already been performed by Howe in his statistical derivation of the production function using data from tow-tank tests. (7)

6.2 Data Sets Used

The first set of data was gathered from towboat logbooks which indicated actual tow characteristics and average attained speeds, net of delays in port and at locks, on the Ohio River. (4) These data cover 224 movements, where a movement is defined as a trip between stops at which the flotilla configuration is changed. The body of the data is shown in Table 6.1.

Since any river, and the Ohio in particular, changes its configuration over its length, it was necessary to determine the relevant average channel characteristics of depth, D, width, W, and stream current, S_w, for each movement in the data set. For this purpose the river was partitioned into three districts:

District 1: Pittsburgh to mile 231

District 2: mile 231 to mile 461

District 3: mile 461 to mile 981.

The assumptions made about the river by the Army Corps of Engineers in reporting the data are shown in Table 6.2.

TABLE 6.1 ACTUAL OPERATING DATA USED

CHARACTERISTIC	DATA SET I	DATA SET II	DATA SET III
Number of Movements	224	24	68
Number of Barges	3 to 27	4 to 8	5 to 18
Flotilla Lengths (ft.)	350 to 1180	390 to 780	390 to 1170
Flotilla Breadths (ft.)	35 to 135	70	35 to 105
Average Drafts (ft.)	1 to 9.3	7.5	2 to 8
Flotilla Types	Semi- and non-integrated	4-barge, fully-integrated	Semi- and non-integrated
Towboat Horsepower	1400 to 3200	1500	3200
Directions of Travel	Upstream and Downstream	Upstream and Downstream	Upstream and Downstream
Years Involved	1958-1961	1949	1964
Months of Year	February, May, August and November	August	All months

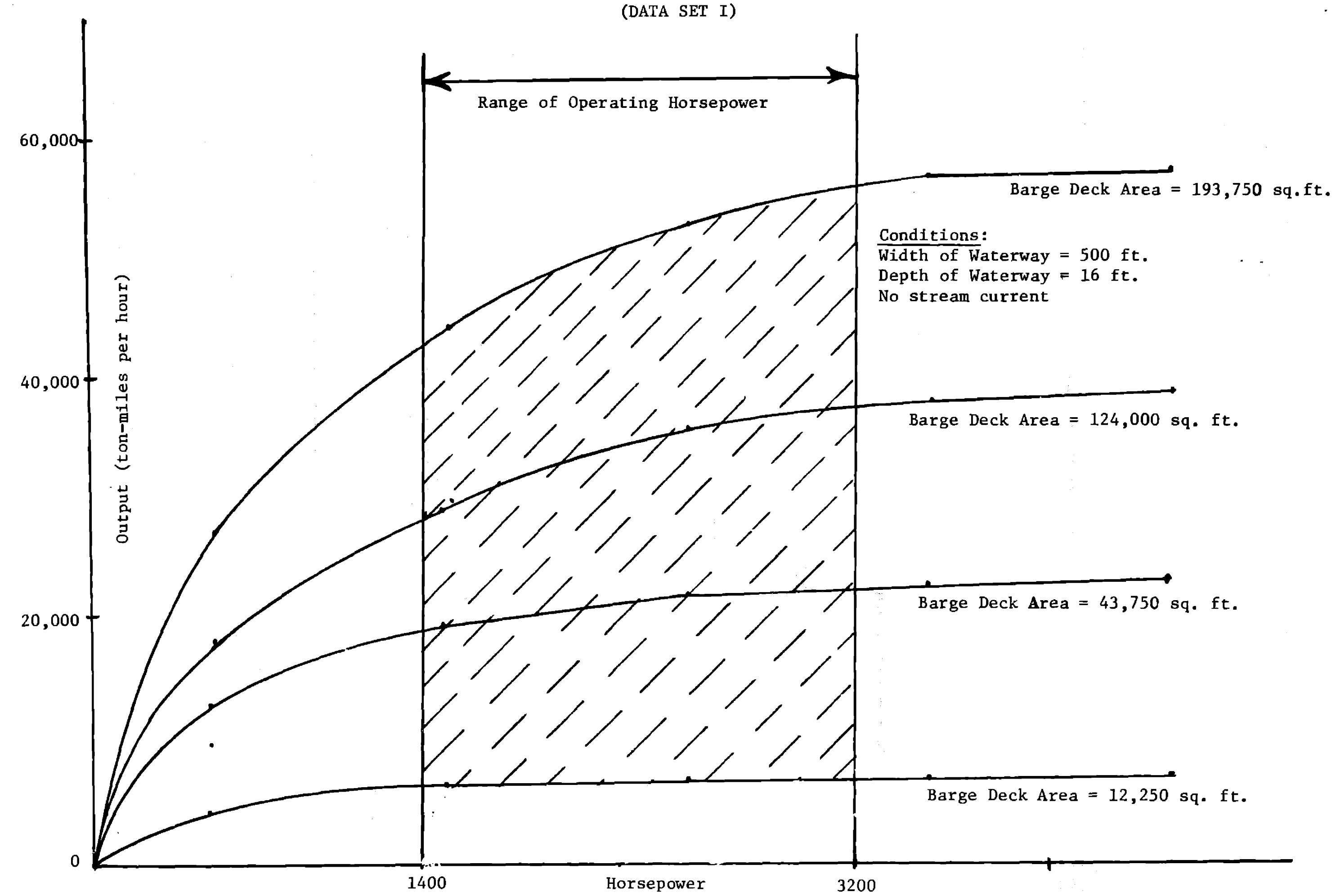
The second set of operating data used was gathered from prototype tests run by the Dravo Corporation and the U.S. Army Engineers on the Mississippi and Illinois Rivers in August, 1949. (7) The characteristics of the data are shown as Data Set II in Figure 6.1. Channel widths ranged from 700 feet to 1500 feet while channel depths ranged from 9.6 feet to 30.2 feet. The stream current velocity was assumed to be 1.36 miles per hour.

The third set of operating data against which the model was tested was gathered from a towboat logbook on the Illinois Waterway and includes all movements during which no delays were incurred for the year 1964. Flotilla configurations had to be assumed, for only the number of barges in the flotilla were recorded in the logbook. Channel widths and depths and stream velocity also had to be assumed by Howe and others (7) who reported the data. The characteristics of the data are shown as Data Set III in Figure 6.1. The channel width was assumed to be 225 feet, the channel depth to be 12 feet, and the stream current velocity to be 1.36 miles per hour.

6.3 Method of Approach Used

To compare the operating data with the predicted results from the model, the ranges of horsepower and barge deck area represented by the operating data were used as inputs to the production function model in order to generate total output curves such as are shown in Figures 6.1, 6.3 and 6.5. From these total output curves, the

FIGURE 6.1 BARGE-TOWBOAT FLOTILLA OUTPUT VS. HORSEPOWER
(DATA SET I)



isoquants for each data set are dervied in the standard manner and are shown in Figures 6.2, 6.4, and 6.6.

Then the optimality criterion is invoked, as defined in terms of the slope of the isoquant, or, equivalently, the marginal rate of substitution, MRS. This is equal to - MP_i/MP_j where i and j are the two inputs to the production function, in this case, horsepower and barge deck area. At optimality, the slope of the isoquant should be equal to the ratio of the costs, so:

$$MRS = \frac{-MP_j}{MP_i} = \frac{-C_j}{C_i} \qquad (6.1)$$

Since we can find the slope of the isoquants from Figures 6.2, 6.4, or 6.6, and since we have firm data on the cost of horsepower (3), we can use this information to derive an imputed cost of the other input, barge deck area. This is the cost that should prevail if the production function model is indeed correct, and if the operators are behaving consistently with the national policy it helps define. Finally, we can determine whether this imputed value is reasonable, given data on barge construction costs and the operating conditions encountered.

6.4 Conclusions Regarding Operating Data

6.4.1 Data Sets I and II

The range of horsepower and barge deck areas used in the operating data for Data Set I is shown cross-hatched on Figure 6.1.

FIGURE 6.2 ISOQUANTS FOR DATA SET I

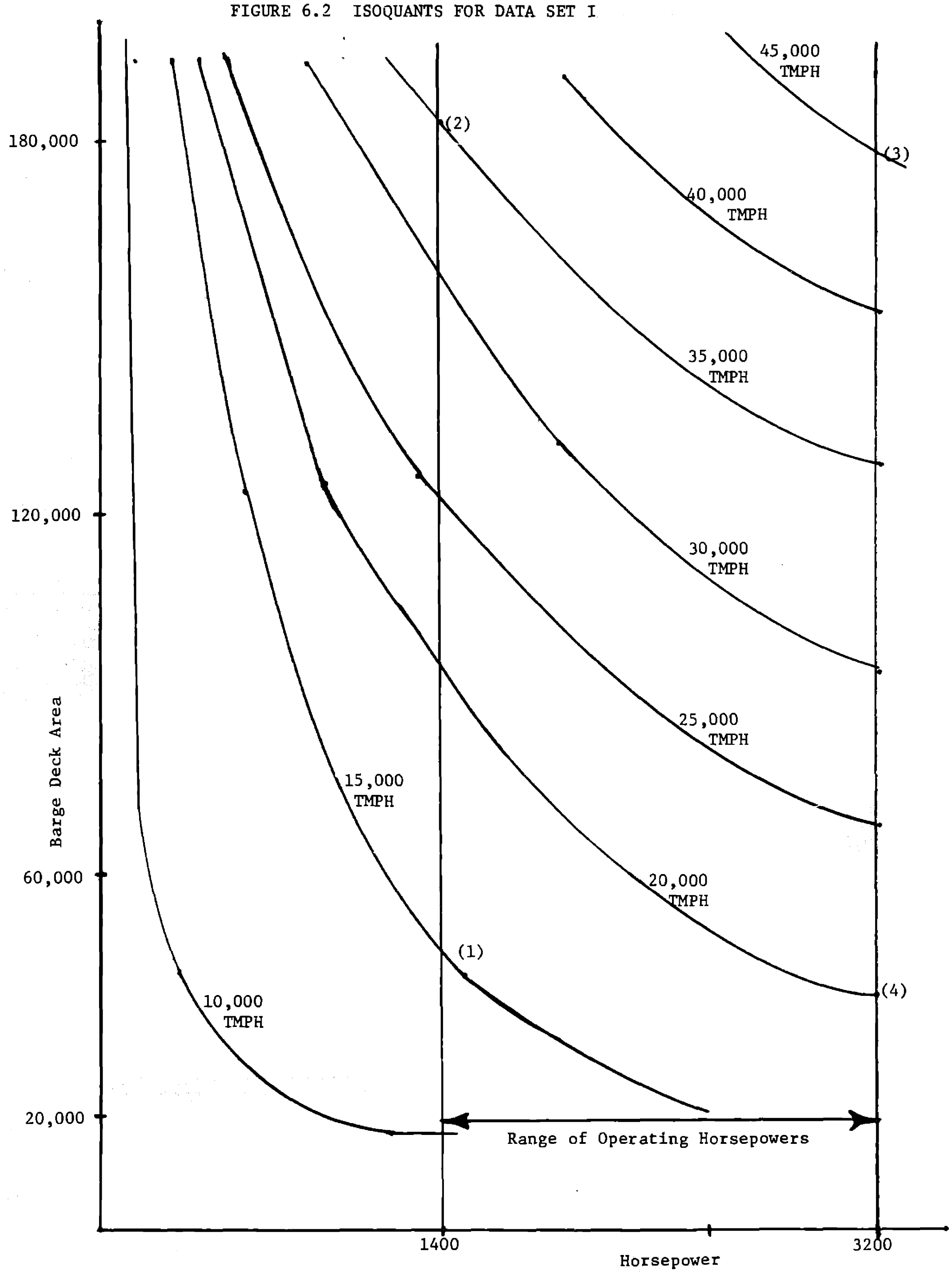
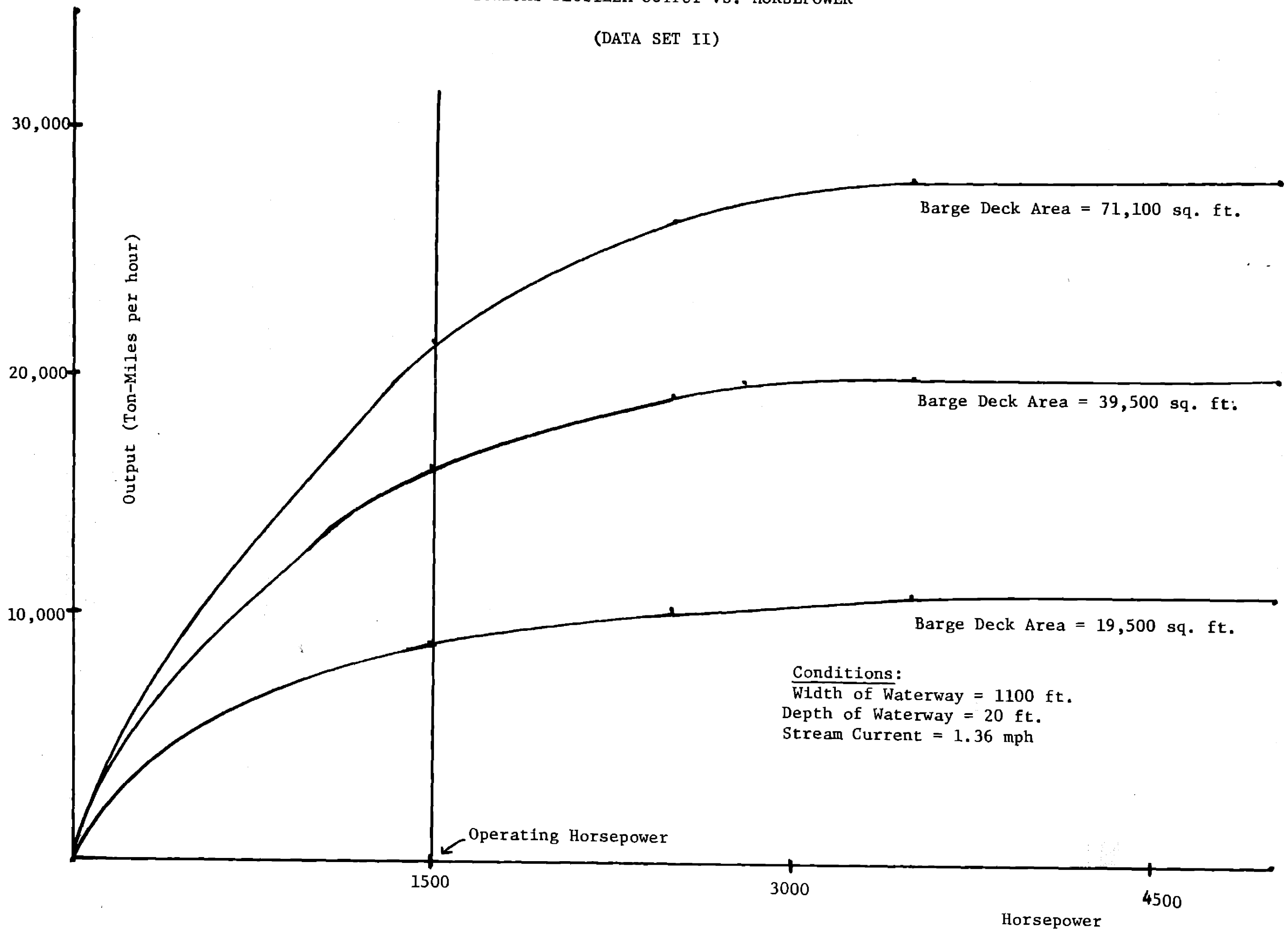


FIGURE 6.3 BARGE-TOWBOAT FLOTILLA OUTPUT VS. HORSEPOWER

(DATA SET II)



Representative points associated with this range are numbered points (1), (2), (3), and (4) on Figures 6.2 and 6.4. At each of these points, the slope of the intersecting isoquant was found. Using the procedure shown below and an estimate of the cost of the horsepower input (3), an imputed cost of one square foot of barge deck area was derived and then compared with the cost of barge deck area construction given in Table 6.3.

For example, at point 4 in Figure 6.2, the slope of the isoquant is approximately $\frac{\text{200 HP}}{\text{4000 Sq.Ft.}}$. That is, if point 4 were an optimal design, the cost of 200 HP should equal the cost of 4000 sq. ft. of barge deck area. At a cost of approximately \$50 per horsepower, the imputed cost of the barge deck area, C_B, is:

$$C_B = \frac{(\$50/\text{HP}) \times (200\ \text{HP})}{4000\ \text{sq. ft.}} = \$2.00/\ \text{sq. ft.}$$

At each of the other points shown, this procedure was employed to derive the results shown in Table 6.4. These imputed costs are of the same order of magnitude as the actual cost of building deck area.

From an inspection of the isoquants alone, one can see that the optimal horsepower to square foot operating ratio is highly dependent upon the output level chosen, and therefore, upon the level of demand to be satisfied. This is to be expected, since we

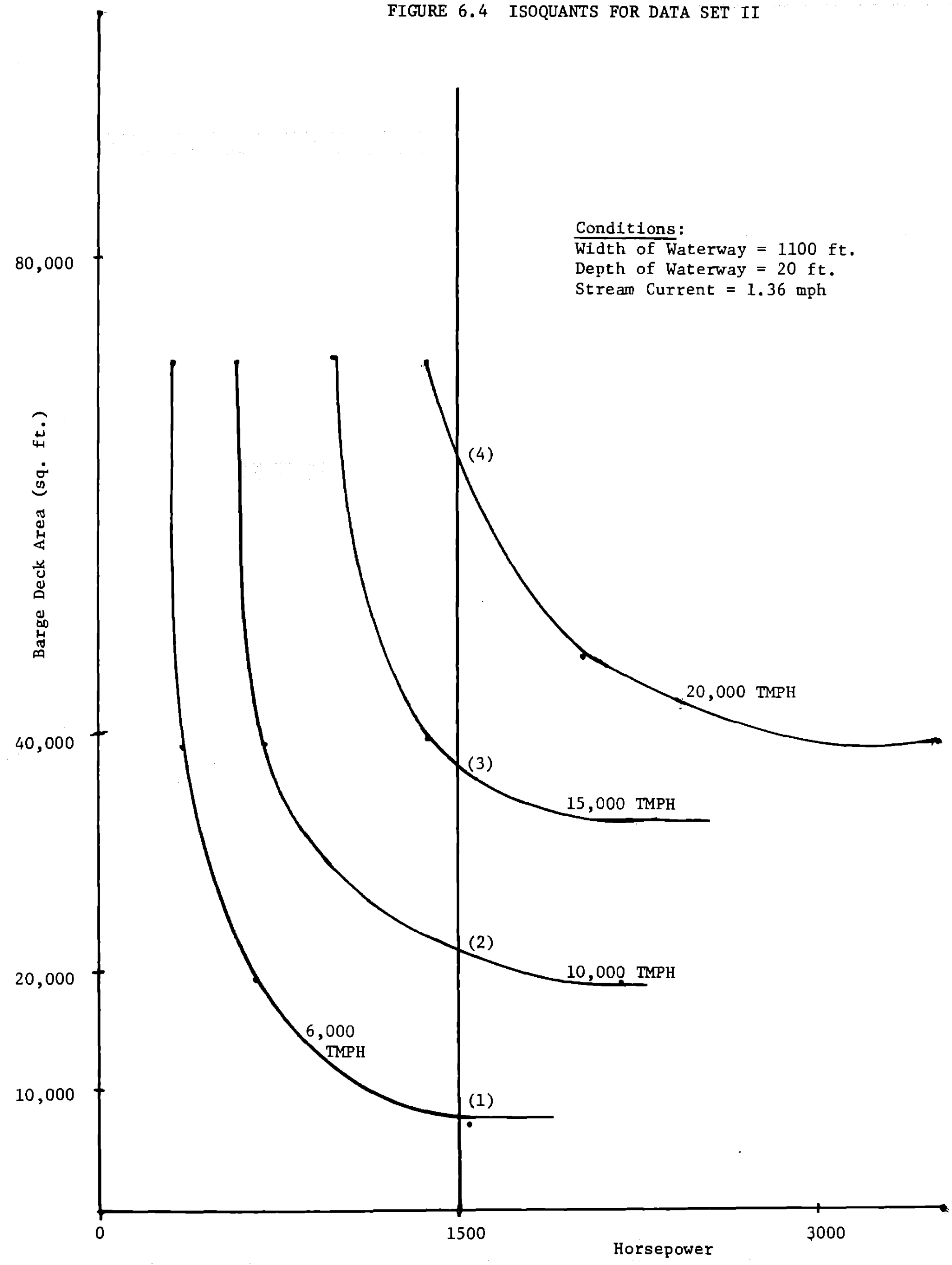
TABLE 6.2 ASSUMED CONFIGURATION OF OHIO RIVER (7)

District	Depth (ft.)	Width (ft.)	Stream Current (miles/hr.)
1	13.2	500	0.0
2	14.5	550	0.0
3	18.3	550	0.0

TABLE 6.3 REPRESENTATIVE COSTS OF BARGE CONSTRUCTION (5)

Country	Cost/($/Sq. ft.)
U.S.A.	4.50
Venezuela	2.80
Colombia	2.60
Spain	3.50

FIGURE 6.4 ISOQUANTS FOR DATA SET II



are dealing, in general, with a non-homogeneous production function. In general, the higher the output level, the higher the optimum barge deck area/HP ratio, relfecting the effects of decreasing returns to scale.

The results for Data Set II are shown in Table 6.5. One can see that the same conclusions can be drawn concerning these results as for Data Set I.

6.4.2 Data Set III

As discussed in Section 6.2, the third set of operating data represents movements of one towboat only during 1964. Since flotilla configurations and waterway dimensions had to be assumed, the validity of the data and consequently the model results derived therefrom are questionable.

However, assuming the above to be correct, one can see from Figure 6.5 that at the horsepower of the towboat (3200 horsepower), no significant tradeoffs exist between horsepower and barge deck area from 14,000 sq. ft. to 42,000 sq. ft., and only a small tradeoff at 114,000 sq. ft. At these lower barge deck areas, one must increase square footage of area to increase output since increasing the horsepower alone will no longer increase output in ton-miles per hour. At 3200 horsepower, we are at the point of zero marginal returns to horsepower.

TABLE 6.4 TABULATED RESULTS FROM OPTIMALITY ANALYSIS (DATA SET I)

Characteristics of Points (Data Set I, Figure 6.2)

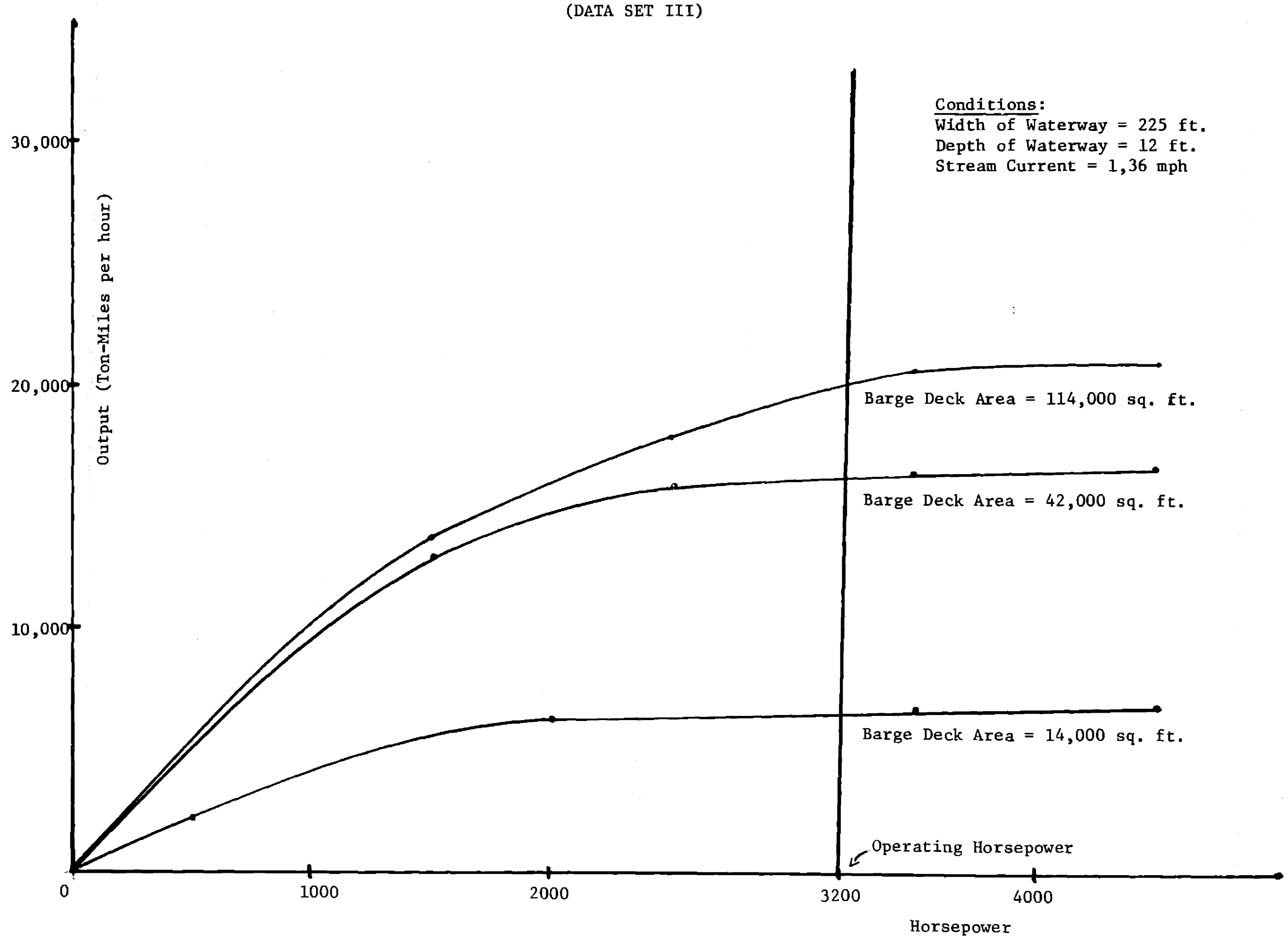
Number	Output Level (ton-miles per hour)	Estimated Marginal Rate of Substitution (sq.ft./HP)	Range of Costs for Barge Deck Area Imputed for Several Points (If the Cost of Horsepower Equals $50/HP) ($/Sq. Ft.)
1	15,000	80	0.60
2	35,000	50	1.10
3	30,000	30	1.90
4	20,000	20	2.50

TABLE 6.5 TABULATED RESULTS FROM OPTIMALITY ANALYSIS (DATA SET II)

Characteristics of Points (Data Set II, Figure 6.4)

Number	Output Level (ton-miles per hour)	Estimated Marginal Rate of Substitution (sq. ft./HP)	Range of Costs for Barge Deck Area Imputed for Several Points (If the Cost of Horsepower Equals $25/HP) ($/Sq. Ft.)
1	6,000	7	3.10
2	10,000	10	2.50
3	15,000	13	1.90
4	20,000	48	0.50

FIGURE 6.5 BARGE-TOWBOAT FLOTILLA OUTPUT VS. HORSEPOWER
(DATA SET III)

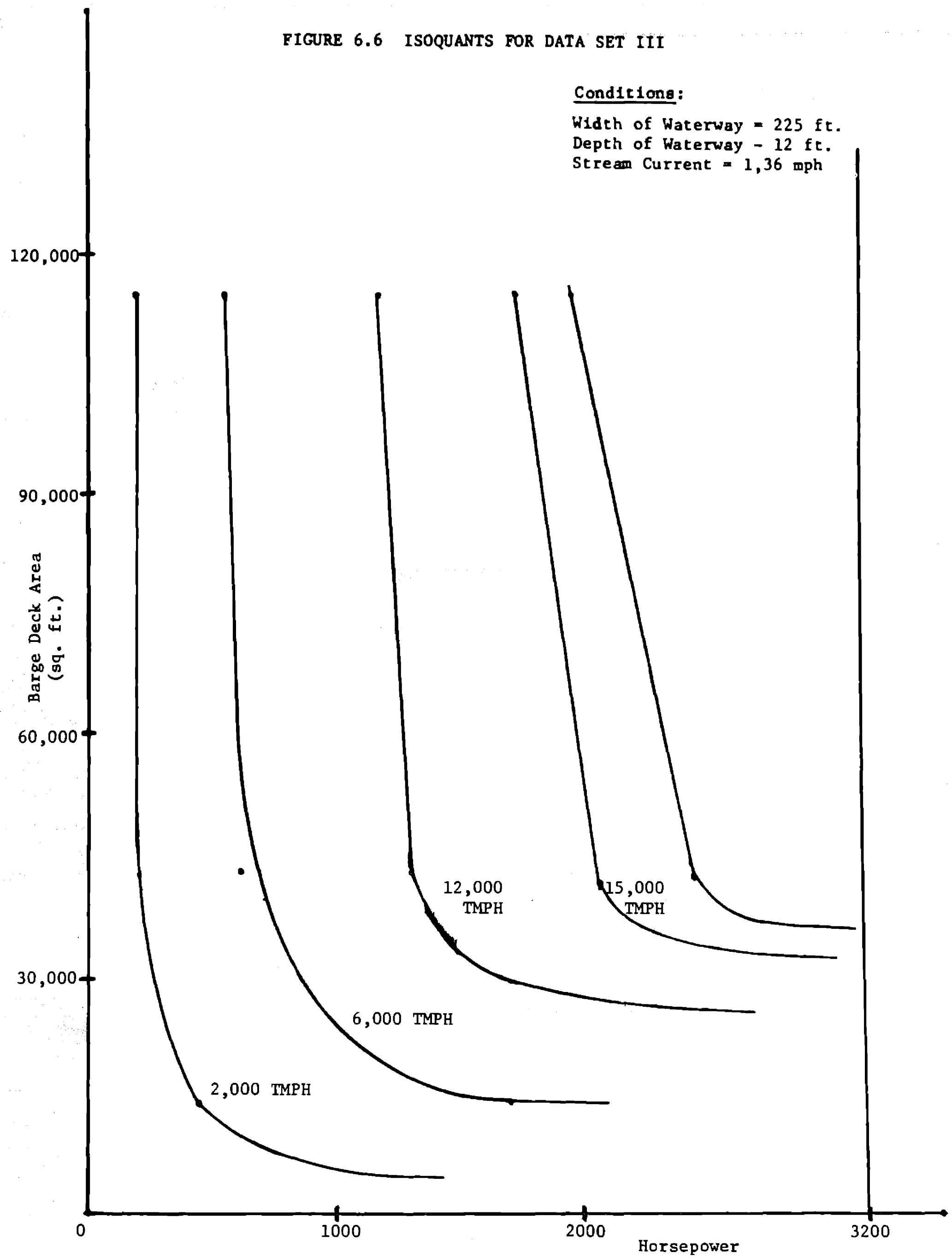


In general, when this operating condition occurs, an optimal allocation of resources is not taking place, since a very high price per square foot of barge deck area is implicitly imputed to this input. However, one must hasten to recall the discussion of Chapter 5, when it was cautioned that what may appear to be non-optimal in terms of the production function only must be viewed in the larger context of a "planning function," where stocks of boats and barges are treated to handle demand, scheduling, and utilization contingencies. In this sense, perhaps the boat, for which we have operating data, forms only one small link in a larger chain of O-D patterns and demand and scheduling complexities of which we are unaware.

6.5 Operating vs. Design Data

The above three sets of data were used as inputs to the model since they represent observations on actual barge-towboat flotilla operations on a specified waterway over a given period of time. This type of operating data is to be distinguished from design data regarding a stock of barges and towboats which can be used in many different combinations, such as is shown in Table 6.6. This latter type of data would be more appropriate to the estimation of a planning function, not to the testing of a production function, since a planning function is concerned with the total stocks of equipment

FIGURE 6.6 ISOQUANTS FOR DATA SET III



held by a firm, such as are represented by the data in Table 6.6. A production function is concerned with actual barge-towboat flotilla configurations when in productive use, i.e., the length and breadth of the barge flotilla and the horsepower of the towboat used to push that specific flotilla. Many different combinations of the barges listed in Table 6.6 could be fitted together to form a barge flotilla and then be pushed by one of the towboats. However, we have no specific data on which of these barges were used with which of the towboats nor the characteristics of the navigable channels over which they operate.

6.6 Conclusions

The above comparison of operating data with the production function model results leads to these major conclusions.

First, the imputed cost per square foot of barge deck area construction derived from the model, using the ranges of operating data as inputs, falls reasonably close to the cost of barge construction in both the U.S.A. and other countries.

Secondly, from an inspection of the isoquants alone, one can see that the optimal horsepower to square foot ratio is highly dependent upon the output level chosen, and, therefore, upon the level of demand to be satisfied. This is to be expected, since we are

TABLE 6.6 DESIGN DATA FROM A COLOMBIAN BARGELINE FIRM (10)

Towboats	Horsepower	Number of Motors
Amalfi	1920	3
Javier Humberto	1920	3
Galeres	1440	3
Dona Maria	1440	3
Quinunchu	1280	2
Cancherazo	800	2
Towboat R-4	280	1
Towboat R-3	175	1
Towboat R-1	150	1

Number of Towboats Having the Given Characteristics	Length (feet)	Breadth (feet)	Draft (feet)
18	140	30	5.5
12	192	40	6.5
4	192	39	6.8
2	192	40	7.6
2	182	39	6.9
2	179	36	5.4
1	165	34	5.5
1	76	26	4.9
1	49	9.8	3.9

dealing, in general, with a non-homogeneous production function. In general, the higher the output level, the higher the barge deck area/horsepower ratio, reflecting the effects of decreasing returns to scale.

CHAPTER 7. SUMMARY AND CONCLUSIONS

7.1 Summary

This thesis illustrates the economic analysis of a production function for inland waterway transportation. An economic analysis was performed which considered diminishing marginal returns to the inputs, returns to scale, the effect of a stream current velocity, and constraints on the length of the barge flotilla. Expansion paths were also derived showing optimal designs for water transport, in terms of optimal ratios of horsepower to barge deck area, in light of prevailing cost and operating conditions. Sensitivity analyses were performed which considered varying relative cost conditions, speed versus cost tradeoffs, and the tradeoffs between investment in dredging and increased horsepower of the towboat.

As a logical extension to the analysis of the production function, a "planning function" was considered to deal with demand factors and scheduling complexities which face an individual firm when deciding upon the optimal stock of capital equipment in which to invest. This was necessary since the production function is a technological relationship only between inputs and output, and thus treats only the supply side of the transportation investment decision.

Lastly, in Chapter 6, various sets of data gathered from towboat logbooks were compared with results obtained from the production function model to determine whether actual operating conditions approximate optimality as defined by use of the model.

7.2 Conclusions

In the economic analysis of the production function, it was found that the curves defining total product as a function of either the horsepower or the barge deck area alone, are strictly concave, reflecting the diminishing marginal productivity of the two inputs, horsepower and barge deck area. With no constraint on the maximum length of the barge flotilla, the production function exhibits increasing returns to scale. When a maximum length for the barge flotilla must be specified, the tow will be subject to increasing returns to scale up to a critical size. Beyond this point, the tow is subject to decreasing returns to scale within a waterway of given depth and width.

Isoquants for the production function, derived from the total product curves, were combined with varying isocost lines to derive straight line expansion paths. The latter, in the case of no stream current and no maximum barge length constaint, were characteristic of a linear and homogeneous production function.

It was found that the primary effect of the existence of a stream current is to distort and lower the total output curves of the production function from the no-stream-current case. The distortion due to the existence of a stream current transforms the production function to a linear, non-homogeneous production function with a linear expansion path which does not pass through the origin. This means that, given the prices of the inputs, the optimal ratio of the inputs to the production function will change as the capital expenditure budget increases.

With the specification of a maximum barge length, this constraint leads to "dominated" total output curves, and thus to the existence of barge deck areas which maximize output. The existence of a maximum barge length constraint will also lead to a distortion of the production function and again transforms the production function into a linear, non-homogeneous function with a linear expansion path which does not pass through the origin.

The combined effect of a stream current velocity and a maximum barge length constraint may or may not transform the production function from homogeneous to non-homogeneous, depending on the specific operating conditions encountered, but the expansion path will remain a straight line.

Varying relative costs for the two inputs, horsepower and barge deck area will shift the expansion paths toward the relatively cheaper input.

It is shown that, for a given barge deck area, there is a value of horsepower which yields a minimum cost per ton-mile per hour. However, deviations from this minimum in the direction of increased horsepower are less costly, in terms of cost divided by output productivity, than are deviations in the direction of less horsepower. Thus, tradeoffs between increased level of service, as defined by speed, and cost can be generated explicitly using the model.

It is shown that definite tradeoffs exist between dredging the given waterway and increasing the horsepower of the towboats which operate on the waterway. Firstly, the tradeoffs are very small until higher output levels are reached. This implies that dredging should be used only for more congested waterways where the volume of movement of goods and relative size of the barge flotilla are large. Secondly, it is shown that dredging to greater and greater depths brings diminishing marginal returns. And finally, since dredging is very expensive, it is cost-effective only for short distances, considerable traffic, or where we are talking about dredging a new canal, where extensive cost savings can be effected.

An inland waterway transport firm may experience increasing returns to scale in its production function (using flows of capital) but decreasing returns to scale in its capital stock-output relationship, (called the "planning function"). Ultimately, the capital stock-output relationship and its scale economies or diseconomies will determine the firm's ability to expand line-haul operations without incurring increasing inefficiency.

Finally, the comparison of operating data with the production function model led to these major conclusions. Firstly, the imputed cost per square foot of barge deck area construction derived from the model, using the ranges of operating data as inputs, falls reasonably close to the cost of barge construction in both the U.S.A. and other countries. Secondly, the optimal horsepower to square foot ratio is highly dependent upon the output level chosen, and therefore, upon the level of demand to be satisfied. In general, the higher the output level, the higher the barge deck area/horsepower ratio, reflecting the effects of decreasing returns to scale.

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