

LAKE MICHIGAN STUDIES
Special Report Number LM 12

CURRENTS IN THE SOUTHERN BASIN

June 1963

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Division of Water Supply and Pollution Control
Great Lakes-Illinois River Basins Project

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1. The first part of the paper is devoted to the study of the properties of the function $f(x)$ defined by the equation

$f(x) = \int_0^x f(t) dt$

It is shown that the function $f(x)$ is continuous and differentiable on the interval $[0, 1]$. The derivative of $f(x)$ is given by the equation

$f'(x) = f(x)$

It is also shown that the function $f(x)$ satisfies the equation

$f(x) = e^x - 1$

TABLES

1. Period of the Inertia Circle
2. Percent of Speed for Station 17

FIGURES

1. Current Meter Stations
2. Two-Hour Envelopes of Speed and Direction, Station 17, Depth 30 Ft.
3. " " " " " 18, " 30 "
4. " " " " " 20, " 50 "
5. " " " " " 20, " 100 "
6. " " " " " 20, " 300 "
7. Central Vector Diagrams
8. Progressive Vector Diagram
9. Prevailing Speed and Direction, Station 17, Depth 30 Ft.
10. " " " " 18, " 30 "
11. " " " " 18, " 100 "
12. " " " " 20, " 50 "
13. " " " " 20, " 100 "
14. " " " " 20, " 300 "
15. " " " " 4, " 60 "
16. " " " " 4, " 90 "
17. Current Pattern and Related Wind Flow
18. Current Pattern and Related Wind Flow

1. The first part of the document is a letter from the President of the United States to the Congress, dated January 1, 1861. It is a very important document, as it sets out the President's policy for the new year. The President states that he is pleased to see the Congress assembled, and that he is confident that the country is in a good position to meet the challenges of the future. He also mentions the recent election of Abraham Lincoln as President, and expresses his confidence in the new administration.

2. The second part of the document is a report from the Secretary of the Treasury, dated January 1, 1861. It provides a detailed account of the financial state of the country at the beginning of the year. The report states that the country is in a sound financial position, with a strong and stable currency. It also mentions the recent election of Abraham Lincoln as President, and expresses confidence in the new administration.

3. The third part of the document is a report from the Secretary of the Interior, dated January 1, 1861. It provides a detailed account of the state of the country's natural resources and land. The report states that the country is rich in natural resources, and that the land is being developed in a responsible and sustainable manner. It also mentions the recent election of Abraham Lincoln as President, and expresses confidence in the new administration.

4. The fourth part of the document is a report from the Secretary of the Navy, dated January 1, 1861. It provides a detailed account of the state of the country's naval forces. The report states that the country has a strong and modern navy, and that it is well-equipped to meet the challenges of the future. It also mentions the recent election of Abraham Lincoln as President, and expresses confidence in the new administration.

5. The fifth part of the document is a report from the Secretary of the War, dated January 1, 1861. It provides a detailed account of the state of the country's military forces. The report states that the country has a strong and modern army, and that it is well-equipped to meet the challenges of the future. It also mentions the recent election of Abraham Lincoln as President, and expresses confidence in the new administration.

INTRODUCTION

This is the twelfth and last of a series of special reports prepared by the Great Lakes-Illinois River Basins Project relating to the probable effects of returning treated metropolitan wastes from Chicago to Lake Michigan. This report presents additional data pertaining to the movement of waters in the southern basin of Lake Michigan, and relates the new data to the earlier findings.

Data from three additional current meter stations, with records from six current meters, have been evaluated, and compared with information from the three meters discussed in Special Report LM 11. Approximately 38,600 half-hour measurements were recorded between December and April 1963 from the nine meters. In addition, about 15,000 readings made with meters set to record continuously have been processed.

The new data are from Stations 17, 18, and 20 located on a line east of Milwaukee as shown on Figure 1.

A study of the available data has failed to reveal any evidence of a well defined current pattern in the southern basin. It is the purpose of this report, then, to draw such conclusions as can be properly made concerning the movement and presence or absence of advective mixing of waters of the southern basin.

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RESULTS

Daily Current Graphs

Figures 2, 3, 4, and 5 show the envelopes of maximum and minimum speeds and directions for each two-hour period during selected six-day periods. One period, February 24 to March 2, 1963 was selected for five meter locations to portray the water movement across the sill area between the southern and northern basins under an ice cover.

Figure 2, Station 17, shows a steady southward flow for nearly 36 hours before the currents shifted to the north for 36 hours. Current velocities were between 0.1 and 0.2 feet per second (fps). During the next two days, the direction changed more or less continuously, exhibiting rotary currents with velocities ranging as high as 0.66 fps. On the last day, the current again moved southward. This station was about 3 miles from shore.

Station 18 is nearly 22 miles from shore and east of Station 17. Figure 3 shows currents at this station, at the 30-ft. depth. During the period shown, rotary currents persisted for six consecutive days. Velocities ranged from nil to more than 0.2 fps. It is interesting to note that the speed varies from near zero to a peak and back again to zero during each complete revolution. The average period of rotation is about 18.1 hours, which is approximately the inertial period, as described in Special Report No. IM 11.

Station 20 did not exhibit rotary currents (Figure 4), although the speed shows a cyclic tendency. Peak speeds up to 1.45 fps occurred. The current generally was from a westerly direction over the six-day period.

Figure 5, Station 20 at the 100-ft. level, shows that the rotary type current can occur at greater depths, although very imperfect as compared to Figure 3. In general, the current was from the west, shifting to the north and remaining from the north over most of the period. Peak velocities reached 1.0 fps.

Figure 6, Station 20 at the 300-ft. level, shows one peak velocity of 1.5 fps but speeds were between 0.1 and 0.2 fps most of the time. In general, the currents were from the northeast to northwest sectors. The tendency toward rotary currents is shown during the last 24 hours, but the prevailing movement was definitely from the north.

1. The first step is to identify the problem. This involves understanding the current situation and what needs to be changed.

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Rotary Currents

Figures 7 and 8 show several classic examples of rotary currents in Lake Michigan. Although these currents may occur during all periods of the year, they are to be expected principally during calm periods when external forces are at a minimum. Figure 7, a set of central vector diagrams, shows five of the complete circles as measured between 4:30 P.M. on February 25 and 11:00 A.M. on March 1, 1963. Figure 3 shows the same data in a different form. Table 1 shows that the average period of five rotary current cycles is 18.1 hours. The theoretical period for an inertial rotation at this latitude is 17.6 hours. Figure 8 shows progressive vector summation diagrams for the same period (February 25 to March 2). The total theoretical displacement was about 6,600 feet in 106 hours.

Prevalence of Movement

On Figure 9, data from Station 17 show a bimodal shallow-water flow near the western shore of the lake. The distribution of prevailing direction is 60 percent from the north and 40 percent from the south. East-west components are small, due to the location of the station near the shore.

Figure 10, Station 18 at the 30-ft. level, shows little dominance in direction. About 65% of the time the direction is from the south. Figure 11, data from the same station at 100-ft. depth, shows a pronounced prevalence of direction from the south, with less than 10% from the north.

Figures 12, 13, and 14 depict data from Station 20 at the 30, 100, and 300-foot levels, respectively. Surprisingly, they show a progressive left hand shift in direction from the upper levels toward the bottom.

In order to place all the data in the same perspective, Figures 13 and 14 of Special Report IM No. 9 were redrawn, and are presented herein as Figures 15 and 16. They show a prevailing movement from the northwest during the May to July 1962 period, at Station 4.

To show relationship between speed and direction, not apparent in Figures 9 through 16, the data from Station 17 have been summarized in Table 2. The data in this table show the relationship of speed to direction in a 20 degree sector, one from the north quadrant and one from the south quadrant, as well

1. *Chlorophyll a* and *Chlorophyll b* were determined by the method of Lichtenthaler and Whistler (1973). The total chlorophyll content was determined by the method of Arar and Cook (1980). The carotenoid content was determined by the method of Lichtenthaler and Whistler (1973). The total carotenoid content was determined by the method of Arar and Cook (1980). The total carotenoid content was determined by the method of Arar and Cook (1980).

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1. 1961-1962

as the total observations recorded. The average speed for all observations was 0.25 feet per second and the dominant direction, 340° - 360° , has an average speed of 0.24 fps. The secondary sector, 160° - 180° , has an average speed twenty percent greater than the speed in the prevailing northerly direction. However, the total flow from the south is still half that from the north. The speed ranges for the individual sectors agreed well with the percentage shown for the total observations and the mean speed. The percentages within a specific speed range exhibited the same type of curve for the data. It is believed that these relationships would hold for all stations, i.e., that the prevailing directions shown on the diagrams are generally indicative of the predominant movements of water.

Synoptic Maps

During the time period when data were simultaneously available from all five current meter stations, several synoptic plots of the two-hour current velocity envelopes were prepared. These plots were made twice daily for upper (50 feet) and lower (100 feet) levels for the times beginning at 0000-0200 hours (CST) and 1200-1400 hours (CST). Figure 17 shows a synoptic map for March 21, 1963. Stations 4, 17, and 18 had data at the 30-ft. level and at Stations 3 and 20 the data shown are for the 50-ft. level. Although some change of direction of flow is likely to occur between the 30-ft. and 50-ft. levels, records from stations where both levels were recorded indicate that this change would not normally be greater than twenty degrees.

The plotted vector is the two-hour average of speed and direction. Figures 17 and 18 are examples of current patterns believed to be resulting from specific wind flow.

Figure 17 shows twenty four-hour prevailing winds and a clockwise current pattern. Figure 18 shows that the water at the 100-ft. level agrees with the upper layers in direction of movement, although flow data at this level are available only at Stations 18 and 20.

The 30-50 ft. chart on Figure 18 shows a variable condition at Stations 3 and 17 near the shore and opposite to the apparent clockwise circulation of the center of the basin.

Additional insight can be gained from the knowledge of sediment distribution. Partical size distribution indicates a flow from the north on the east shore of the lake as far as

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3. The third part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of the treasurer. The names are listed in alphabetical order, and the addresses are given in full, including the street, city, and state.

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6. The sixth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of the assessor. The names are listed in alphabetical order, and the addresses are given in full, including the street, city, and state.

7. The seventh part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of the collector. The names are listed in alphabetical order, and the addresses are given in full, including the street, city, and state.

8. The eighth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of the recorder. The names are listed in alphabetical order, and the addresses are given in full, including the street, city, and state.

9. The ninth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of the surveyor. The names are listed in alphabetical order, and the addresses are given in full, including the street, city, and state.

10. The tenth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of the engineer. The names are listed in alphabetical order, and the addresses are given in full, including the street, city, and state.

11. The eleventh part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of the architect. The names are listed in alphabetical order, and the addresses are given in full, including the street, city, and state.

Indiana Harbor. The offshore formation of dunes (under water) in the Indiana Harbor area point to the NNE and show a northward movement of water. The sediment distribution agrees with the prevailing flow from the south at Station 4.

Conformal current motion in the southern basin would show that northwest winds which would pile water on the eastern shore would produce a movement around the southern part of the basin and northward along the western shore (1). This movement satisfies the continuity conditions.

ANALYSIS OF RESULTS

Daily Movements

Figures 2 to 6 illustrate the great variability which can occur from station to station as well as the clarity of current patterns which can be shown on a two-hour basis. Figure 17 shows a period in which the anticyclonic whirl in the southern basin was strong and extending beyond the limits of the basin. There is no evidence of any flow from the north on the west shore. From the pattern indicated in Figure 17 it appears that there is no restriction to movement across the basin sill. In fact, Figure 18, the 100 ft. level would indicate that the upper 100 feet of water moves freely between the two basins during this type of circulation. Speeds indicate a slow but much larger mass moving southward into the basin whereas the outflow is a smaller mass but much faster.

A strong northwesterly wind flow was apparently related to this current pattern. This type of anticyclonic flow appears to occur when similar wind data are available. No attempt was made to determine the length of time required to change one current pattern to a new pattern.

Figure 18 at the 100-ft. level shows that the deep water flow moves in the same type of flow as the upper levels. It appears that the anticyclonic flow also occurs in the deeper layers during this period of the year. Speeds at the 100-ft. level were about the same as for the upper layers at the same station.

Figure 18 at the 30-50 ft. level shows an anticyclonic circulation in the main part of the basin but a complete reversal along the west shore of the basin. A light to moderate southwesterly wind persisted through the day, as well as during the preceding two days, and may be responsible for the reverse inshore flow. This pattern was also repeated at other periods for which synoptic current and wind observations were available.

During much of the synoptic study period heavy ice covered the central and northern portions of the lake. Late in February it was estimated that up to 95 percent of the entire lake was ice covered. In March there was a sharp break in the cold weather and temperatures rose to well above normal. Prevailing westerly winds and some periods from the southwest helped to clear the southwest section of the lake early in the month and by the third or fourth week most of the southern basin was free of solid ice cover. It

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 132. *Chlorophyll ayz* (Chl *ayz*)
 133.

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840. 84

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is noteworthy that current patterns related to wind flow in February had the same relationships as were found in late March. It did not appear that the ice cover was important in changing or shifting the current patterns from the observed wind-current relationships during the ice-free periods.

The winter current pattern indicated in Special Report LM No. 11 and related to wind flow has been given further confirmation by the data from the three additional stations, as reported herein.

Rotary Currents

As shown in Figures 3, 7 and 8, rotary currents are a part of the general lake circulation. Both Sverdrup and Defant give illustrations of these occurrences in the oceans (2)(3). Although currents of an inertia period were long suspected it was not until 1936 that they were actually noted in the ocean. Defant suggests that the rotary currents found by Gustafson and Kullenberg (2, p. 439) may be related to inertia waves. During the period when the rotary currents were found in the lake the temperature structure was isothermal and the lake had an ice cover. Station 4, May to July 1962, also indicated the presence of these rotary currents. The large eddy mentioned in Special Report LM No. 11 may also have been the inertia-type rotary current; however, its period was apparently interrupted by another pulse or increase in flow. The period was near 18 hours. These rotary currents, in themselves, appear to be of little or no consequence as there is a very small transport involved. This very aspect, of no transport, is of considerable concern when the question of the movement of pollutants or other materials are considered. Present studies show that although calm conditions may permit a buildup of an effluent, a rotary current can do likewise. Both Sverdrup and Defant stress that this type of inertia current frequently occurs during the calm after the passage of a storm front. Thus, the great amount of energy supplied to the lake can create inertia-period rotary currents. Rotary currents do not appear simultaneously everywhere on the lake. They more likely will occur in an area which is not a part of the dominant current system but rather in an area of temporary calms. Significantly, they are more likely to occur on the sheltered side of the lake during ice-free periods rather than on the upwind side.

The ice cover over the lake during the winter of 1962-63 provided the exceptional case of observing water movements not

1. The first part of the report is a general introduction to the subject of the study. It discusses the importance of the study and the objectives of the research.

2. The second part of the report is a detailed description of the methodology used in the study. It includes information about the sample, the data collection methods, and the statistical analysis.

3. The third part of the report is a discussion of the results of the study. It compares the findings with the previous research and discusses the implications of the study.

4. The fourth part of the report is a conclusion and a list of references. The conclusion summarizes the main findings of the study and provides recommendations for future research. The references list the sources of information used in the study.

5. The fifth part of the report is an appendix. It contains additional information that is not included in the main body of the report, such as raw data, detailed calculations, and additional figures.

6. The sixth part of the report is a bibliography. It lists the sources of information used in the study, including books, articles, and other documents.

7. The seventh part of the report is a list of figures. It includes a description of each figure and a reference to the page where it can be found.

8. The eighth part of the report is a list of tables. It includes a description of each table and a reference to the page where it can be found.

9. The ninth part of the report is a list of abbreviations. It includes a description of each abbreviation and a reference to the page where it can be found.

under the direct influence of the wind. Although current speeds are not exceptionally high, there were relatively few calm periods (less than .03 fps). Energy supplied probably comes from pressure exerted on the ice field by the wind, temperature differentials or stress exerted by variations in atmospheric pressure on the ice.

Diffusion or Dispersal

Recent diffusion dye studies on Lake Huron using dye and drogues pointed up certain aspects that were not found during the Lake Michigan Drogue Study (see Special Report No. LM 10). The major phenomenon not found during this period was the "slick." Slicks or taches d'huile are common to all lakes during moderately calm weather (4). Slicks found on Lake Huron showed that an effluent can be moved with no dispersion. Similar patterns, during stratified conditions, can also occur in Lake Michigan.

Diffusion or dispersal in the longitudinal or vertical axis varies considerably from day to day or during periods of the year. In general, dispersal of particles varies considerably, ranging from no dispersal during periods when slicks occur to great vertical mixing components during the convective overturn in spring and fall. Large scale longitudinal mixing probably occurs during severe weather conditions when strong winds persist. Present studies by the Project and other groups, using dye and drogues find, in general, that mixing during most periods of the year is small.

Long Term Movements

The daily synoptic flow during the winter reinforces the previous hypothesis concerning the long term winter movements in the southern basin. In general, the circulation was anticyclonic (clockwise) in the southern basin with a northerly inflow on the east side of the lake and an outflow on the west side.

Figures 15 and 16 for May-July 1962 show an apparent reversal of the winter 1962-63 pattern. There is reason to believe that a seasonal shift in pattern would occur with a gradual shift in the mean wind flow from winter to summer.

Although certain current patterns appeared to develop and be maintained during specific wind regimes the wind systems can and do change. It would appear that if the wind flows changed for a sufficient period of time there could be counter-clockwise patterns in the winter and clockwise patterns in the summer.

SUMMARY OF ALL PHYSICAL STUDIES

The analysis of nearly 55,000 current observations, mostly winter data, since May 1962 in the southern basin of Lake Michigan has given new insight as to the water movements in the basin.

The data was analyzed by a plot of the two-hour speed and direction envelopes, plotting of synoptic data, graphs of prevailing speed and direction and vector diagrams. The detailed patterns of water movement in the southern basin are still only partially known but the influence of the physical factors on the fate of pollutants are now known in some detail.

In mid-summer a thermocline develops in the southern basin and persists until late fall. Since the thermocline develops rapidly with the onset of summer it is below the fifty foot level in a few weeks. A diffuser site in water depths less than 50 feet would thus be in the epilimnion water for most of the summer and fall months. An effluent which is lighter in density would remain in or on top of the epilimnion. Mixing in the epilimnion no matter how severe, would rarely occur with the lower layers because of the existence of the thermocline. During periods of slicks, which occur in the summer months, any effluent discharged into the upper layers which is lighter than the surrounding water mass would tend to concentrate rather than have any tendency toward dispersion. Drogue studies in the spring of 1963 show that there is no great tendency toward dispersion. In fact, after initial dilution, great or small, only marked meteorological changes would produce sudden mixing in the horizontal or vertical components. Normal turbulent mixing by the moving water mass would account for the dilution over a period of time.

If an effluent were heavier than the upper water mass it would tend to sink into the hypolimnion with little or no mixing. However, upwelling could bring this concentrated effluent into the vicinity of beaches or water intakes. An effluent which has an adjusted density such that it would lie on the thermocline could be brought to the water intakes during periods of upwelling, by internal waves, or by rotary Kelvin waves. Summer currents would usually carry an effluent toward the south but could move in any direction at random. In general, only onshore winds would carry the surface waters directly toward the beaches. An offshore wind would produce upwelling and bring bottom waters to the surface and in the vicinity of beaches or water intakes.

THEORY

The theory of the present work is based on the assumption that the system under consideration is in a state of equilibrium. This assumption is valid for a wide range of conditions, and it allows us to derive a set of equations that describe the behavior of the system. The first of these equations is the continuity equation, which states that the total mass of the system is conserved. This equation is written as follows:

$$\frac{d}{dt} \int_V \rho dV = 0$$

where ρ is the density of the system, and V is the volume of the system. The second equation is the momentum balance equation, which states that the total momentum of the system is conserved. This equation is written as follows:

$$\frac{d}{dt} \int_V \rho \mathbf{v} dV = 0$$

where \mathbf{v} is the velocity of the system. The third equation is the energy balance equation, which states that the total energy of the system is conserved. This equation is written as follows:

$$\frac{d}{dt} \int_V \rho E dV = 0$$

where E is the energy of the system. These three equations are the basic equations of the theory, and they are used to derive the equations of motion for the system. The equations of motion are derived by taking the time derivative of the continuity equation, the momentum balance equation, and the energy balance equation, and then using the chain rule to express the time derivatives in terms of spatial derivatives. This process results in a set of partial differential equations that describe the behavior of the system. These equations are the equations of motion, and they are the main results of the theory.

During the winter period an effluent which rises or sinks will not mix any more readily except during high wind conditions. Water temperatures in mid-winter have decreased just below maximum density and thus, no further convective mixing occurs. Currents found in the winter of 1962-63 indicate a clockwise rotation moving the water in a general northward direction near Chicago.

Vector diagrams indicate that rotary currents, as long as six consecutive days, will keep a water mass in one general area. An effluent discharged during such periods would tend to accumulate heavily in the vicinity of the discharge point.

The total picture of the influence of the physical factors on the fate of effluents discharged into the lake would indicate that a great variety of conditions exist which would tend to permit concentrated effluents to move to water intakes, beach areas, or other points of water use, during any period of the year.

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2. Sverdrup, H.U. et al. The Oceans. Prentice-Hall, New York (1946). p. 1049.
3. Defant, A. Physical Oceanography, Vol. 1. Pergamon Press, New York (1961). p. 729.
4. Hutchinson, G.E. A Treatise on Limnology. John Wiley and Sons, New York (1957). p. 1015.



TABLE 1

Period of the Inertia Circle*

| Circle No. | Start | | End | | Period in Hours |
|-------------------------------------|-------|---------|------|---------|-----------------|
| | Time | Degrees | Time | Degrees | |
| 1 | 1630 | 56° | 1200 | 37° | 19.5 |
| 2 | 1200 | 37° | 0630 | 37° | 18.5 |
| 3 | 0630 | 37° | 2230 | 36° | 16.0 |
| 4 | 2230 | 36° | 1530 | 42° | 17.0 |
| 5 | 1530 | 42° | 1100 | 34° | <u>19.5</u> |
| Average Period | | | | | 18.1 |
| Disregarding No. 1 - Average Period | | | | | 17.6 |
| Theoretical Period, 43° 00 N | | | | | |
| Latitude - 17.5 hours | | | | | |

*Figure 7

TABLE 2

Percent of Speed for Station 17

| Speed in
feet per second | Percent of Total
Observations | Percent of
340°-360° | Percent of
160°-180° |
|-----------------------------|----------------------------------|-------------------------|-------------------------|
| 0 - 0.1 | 25.0 | 15.0 | 12.9 |
| 0.2 | 37.0 | 39.5 | 33.8 |
| 0.3 | 20.0 | 31.9 | 26.3 |
| 0.4 | 4.0 | 4.5 | 6.7 |
| 0.5 | 4.0 | 3.2 | 4.0 |
| 0.6 | 3.5 | 2.0 | 4.3 |
| 0.7 | 2.5 | 0.5 | 4.6 |
| 0.8 | 1.5 | 1.0 | 3.2 |
| 0.9 | 1.0 | 0.5 | 1.6 |
| 1.0 | --- | 0.7 | 1.3 |
| 1.1 | --- | --- | 1.1 |
| Total Observations | 5441 | 915 | 373 |
| Mean Speed | .25 fps | .24 fps | .30 fps |

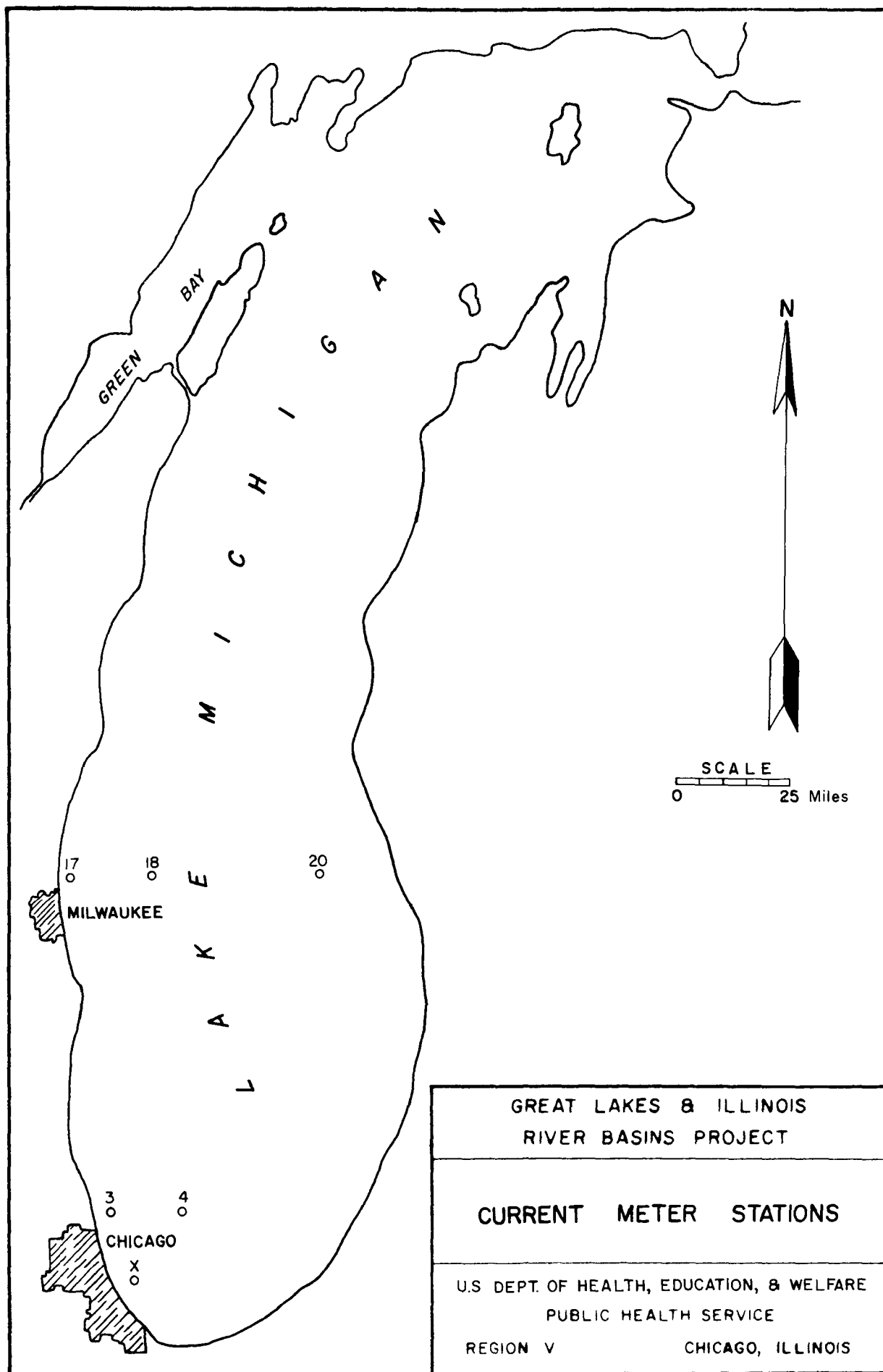


FIGURE 1

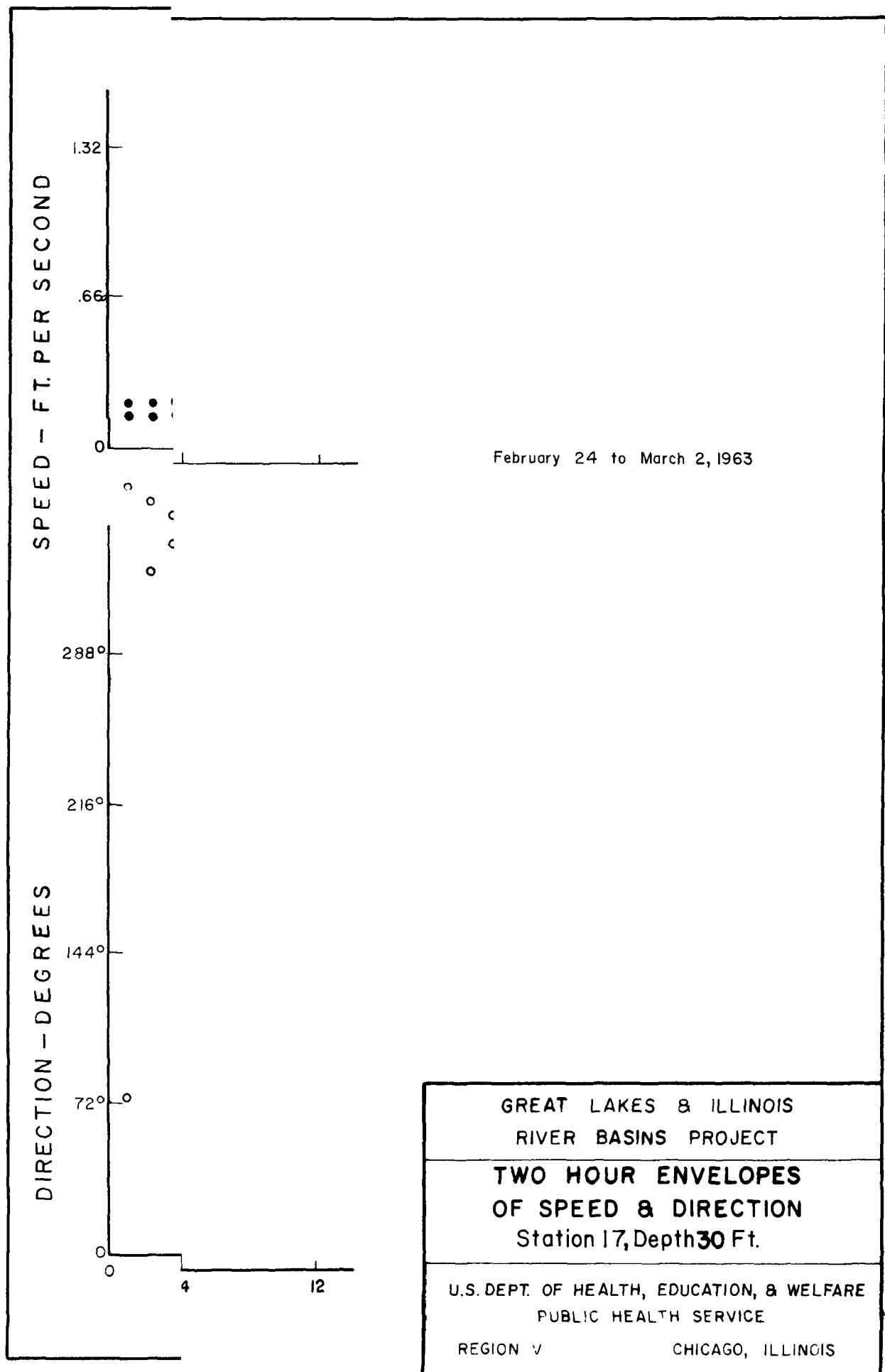


FIGURE 2

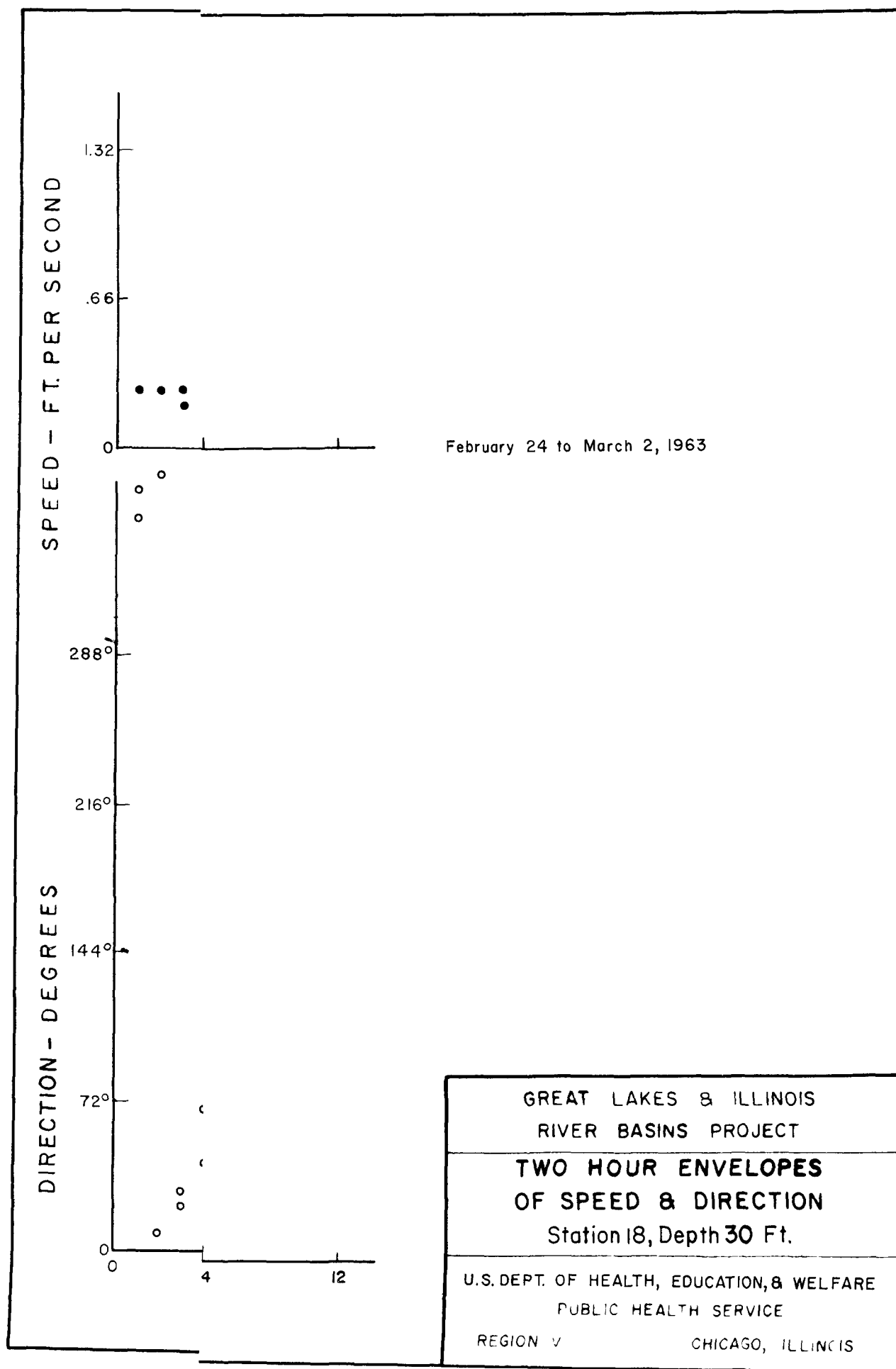


FIGURE 3

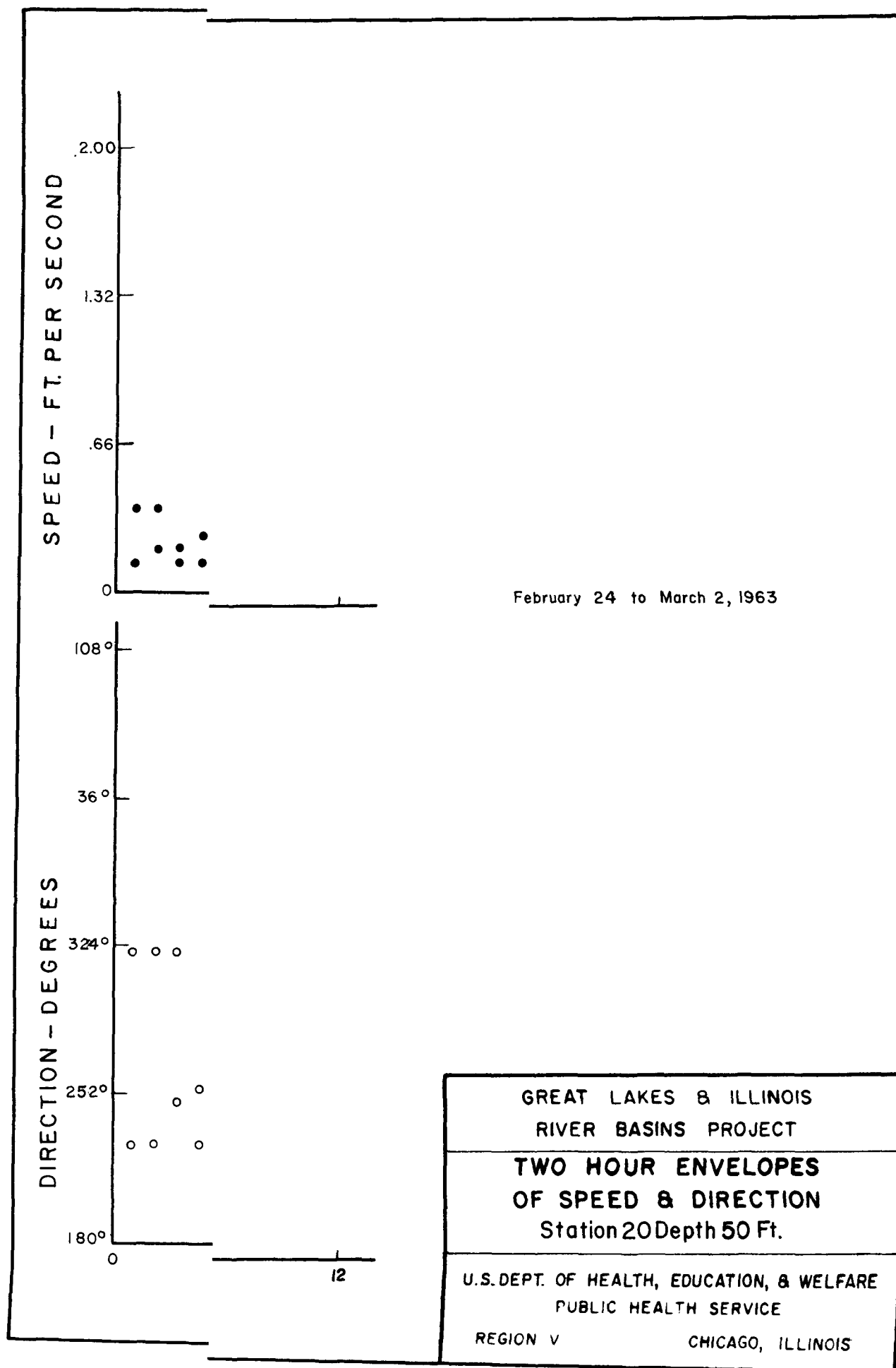


FIGURE 4

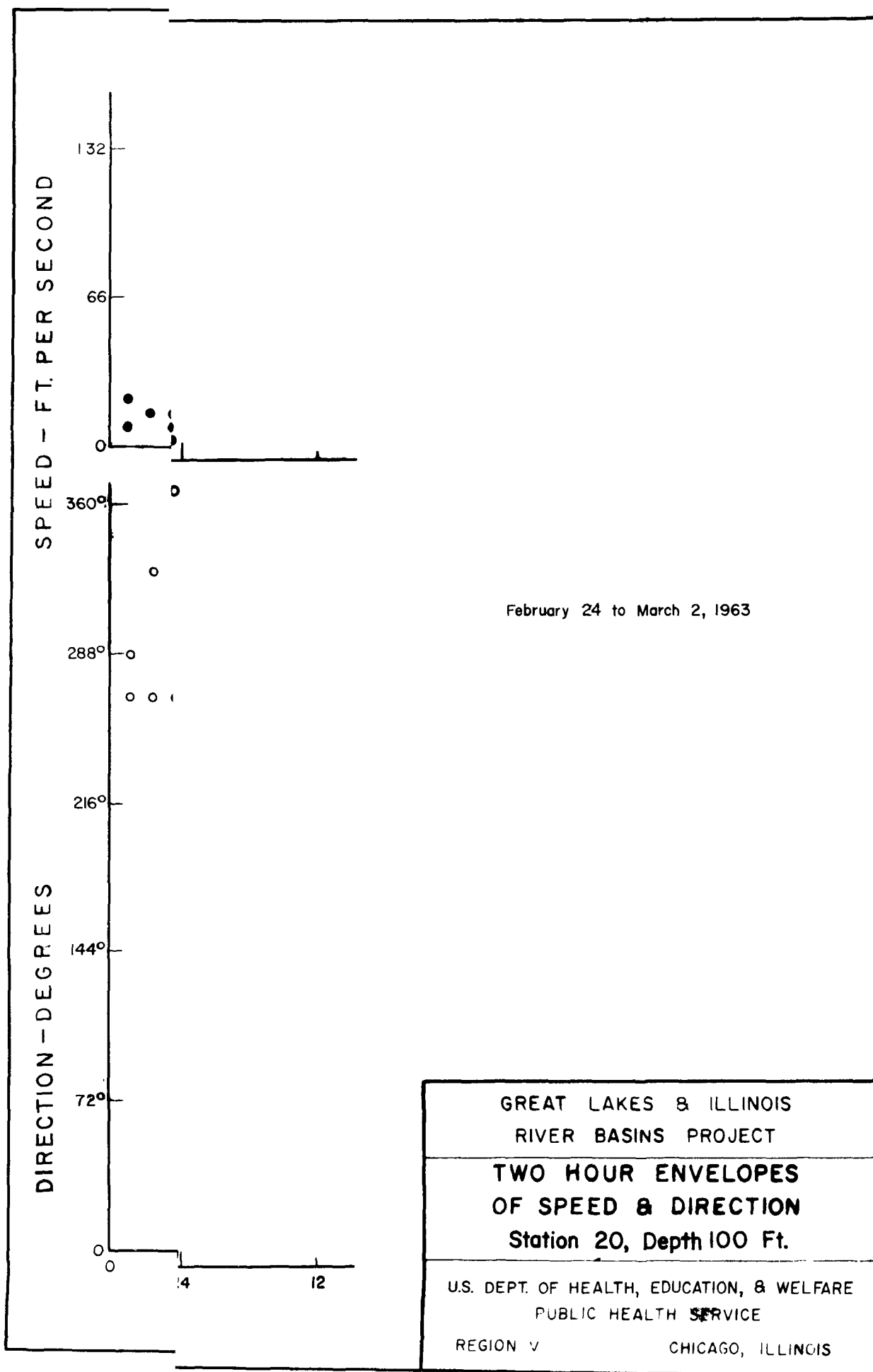


FIGURE 5

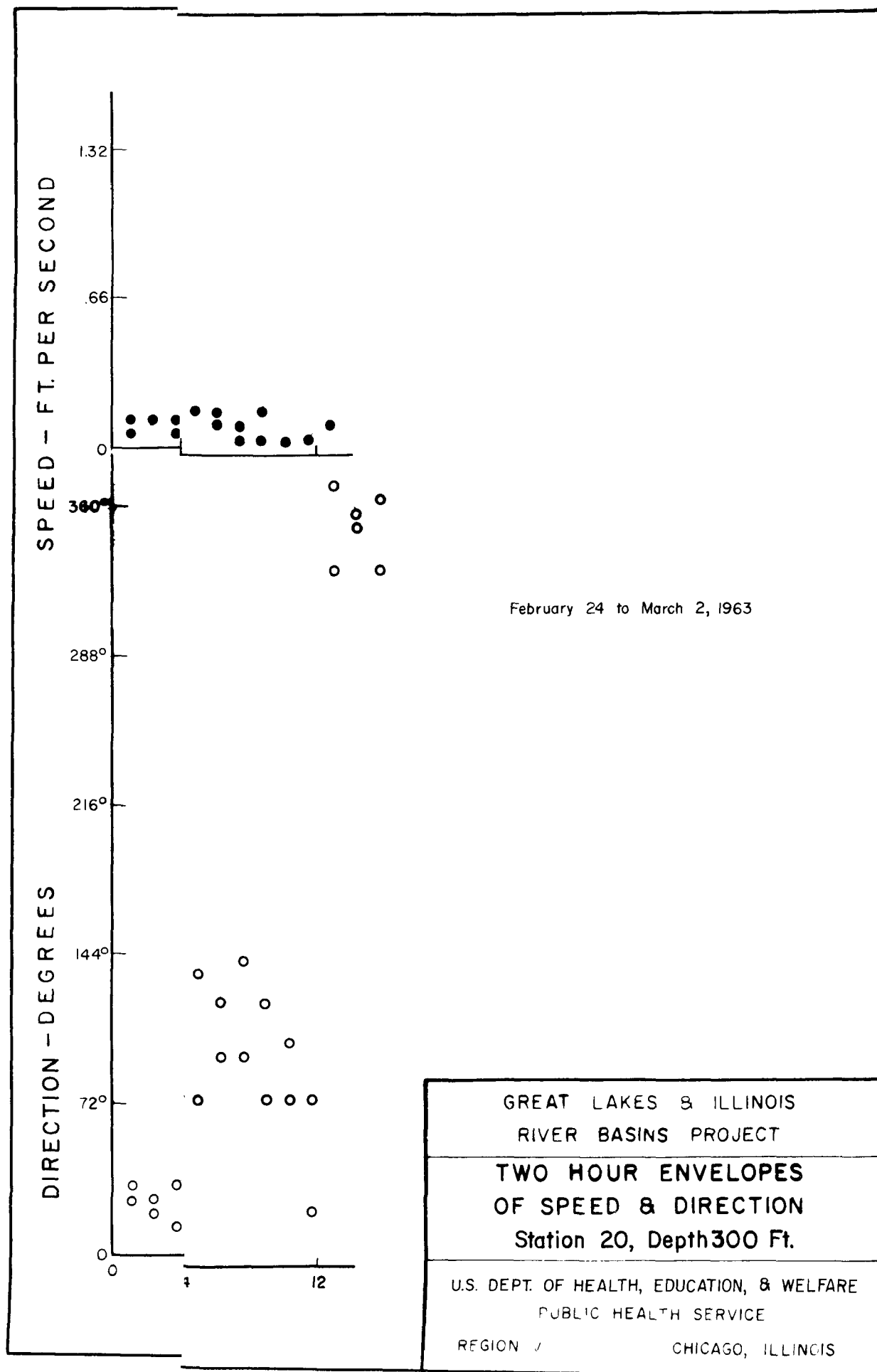


FIGURE 6

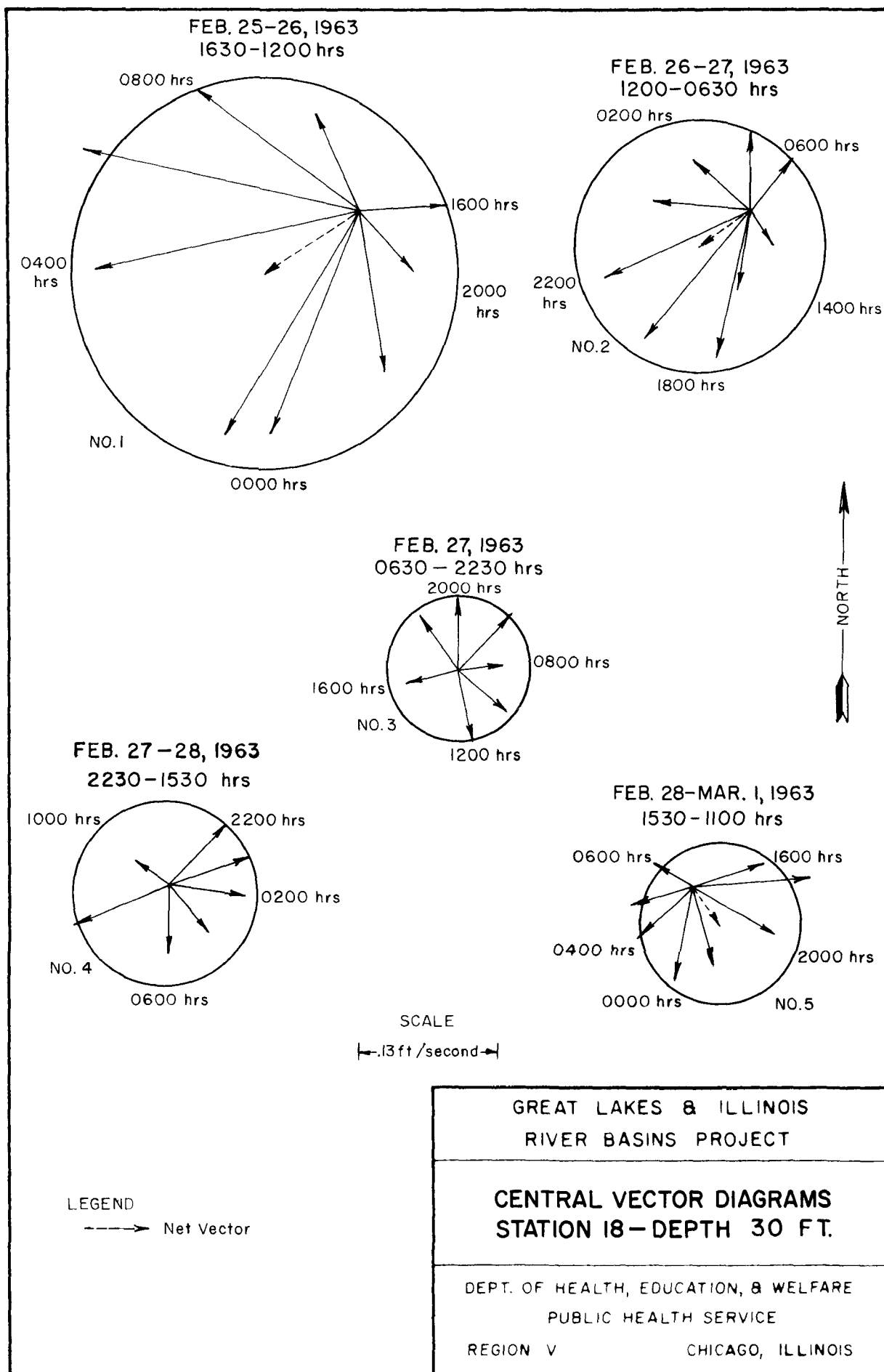


FIGURE 7

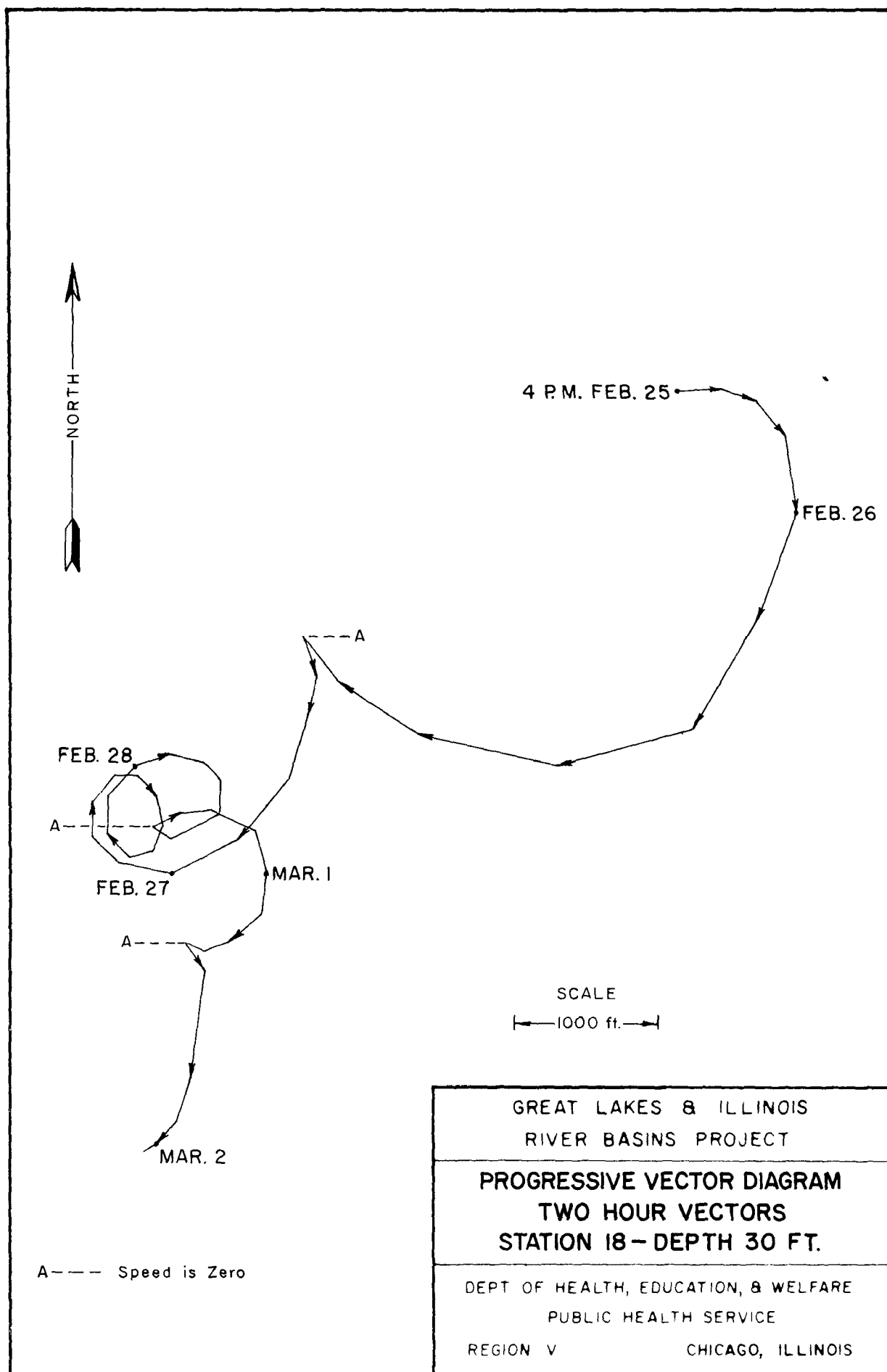


FIGURE 8

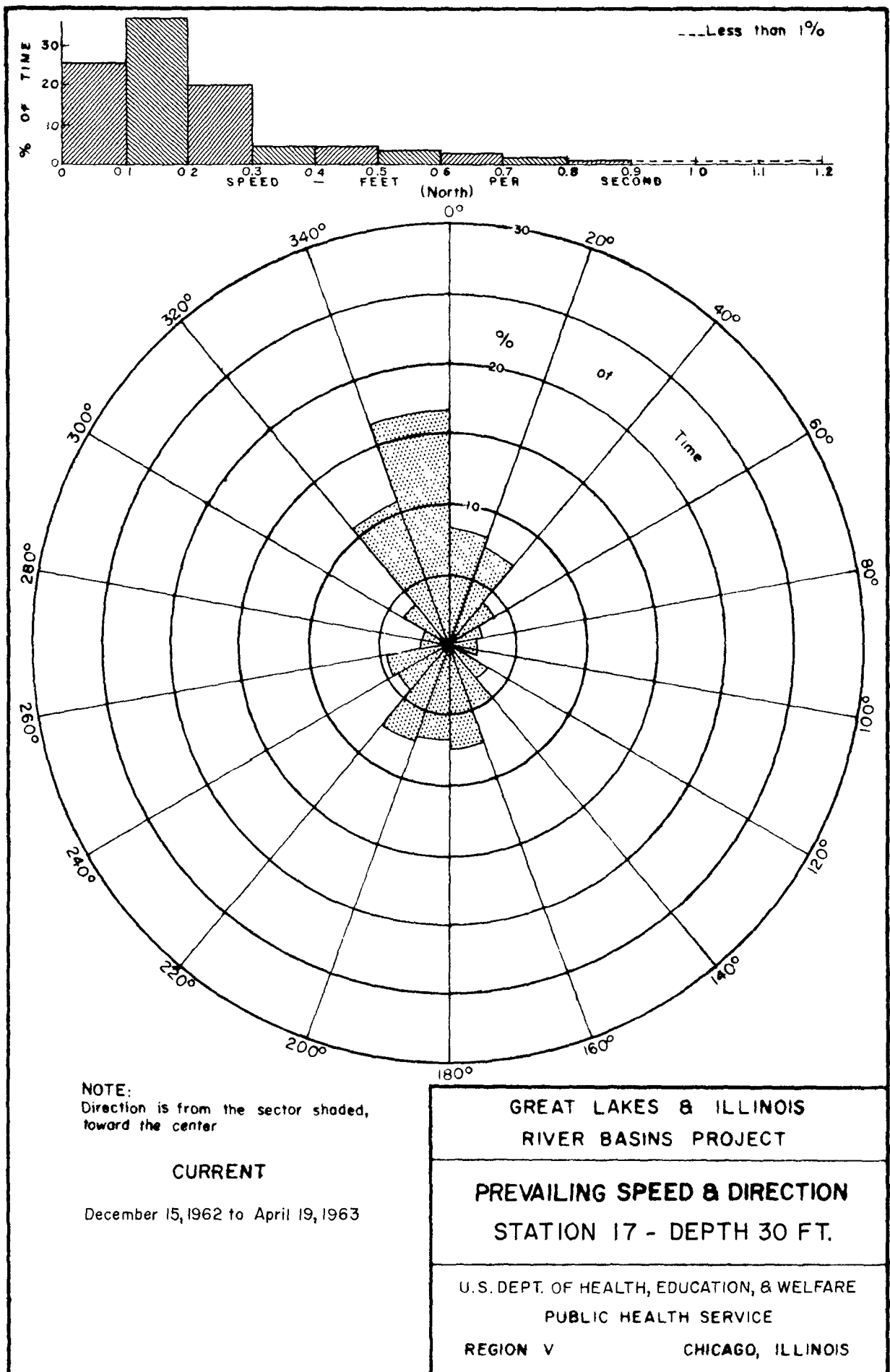
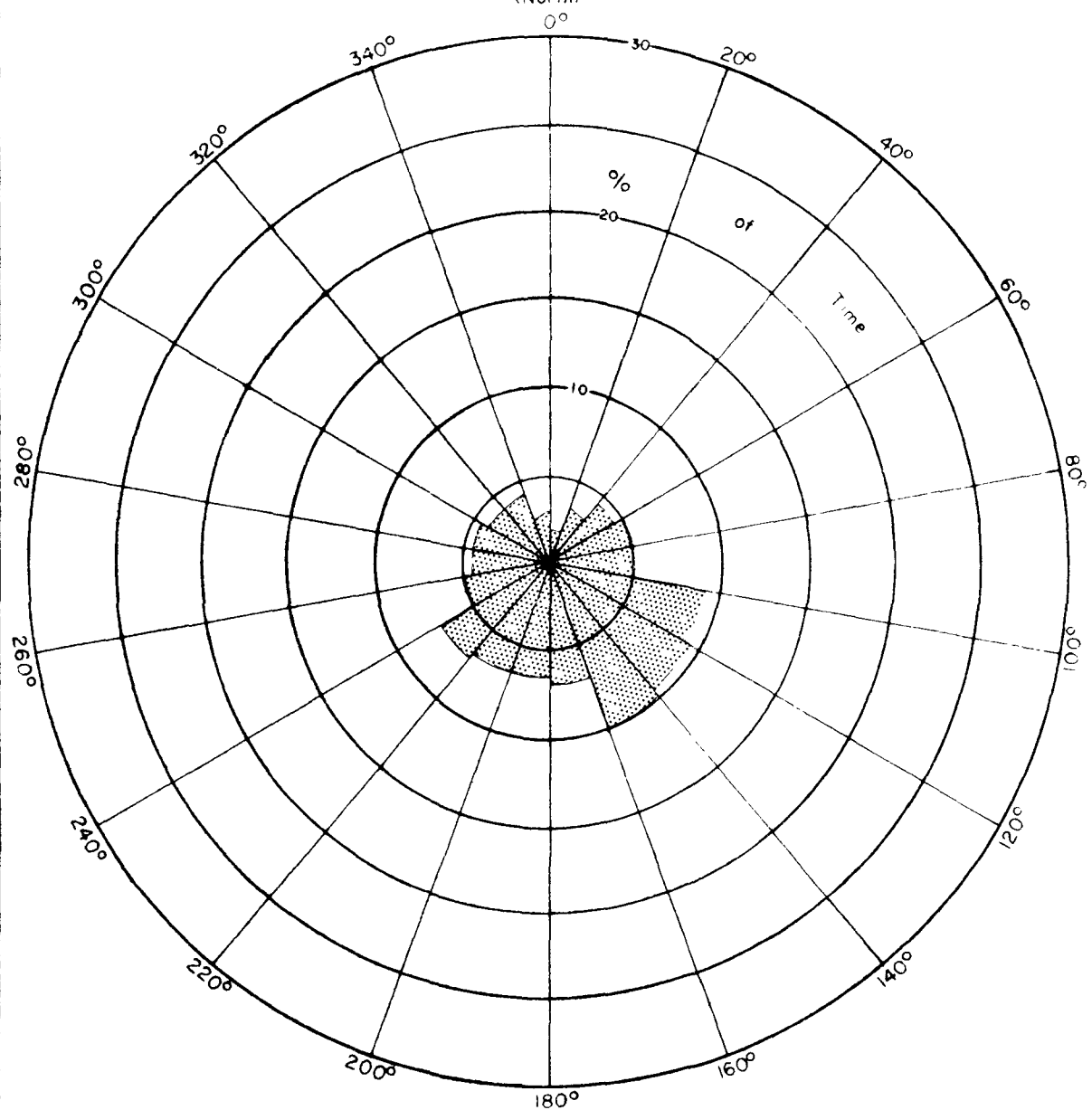
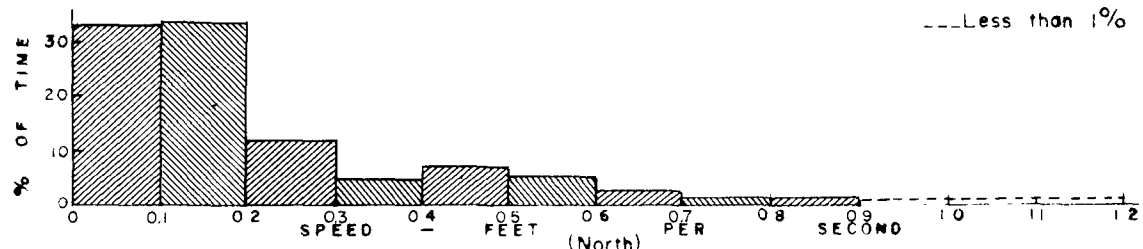


FIGURE 9



NOTE:
Direction is from the sector shaded,
toward the center.

CURRENT

DEC. 5, 1962 TO APR. 20, 1963

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION STATION 18 — DEPTH 30 FT.

U. S. DEPT OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 10

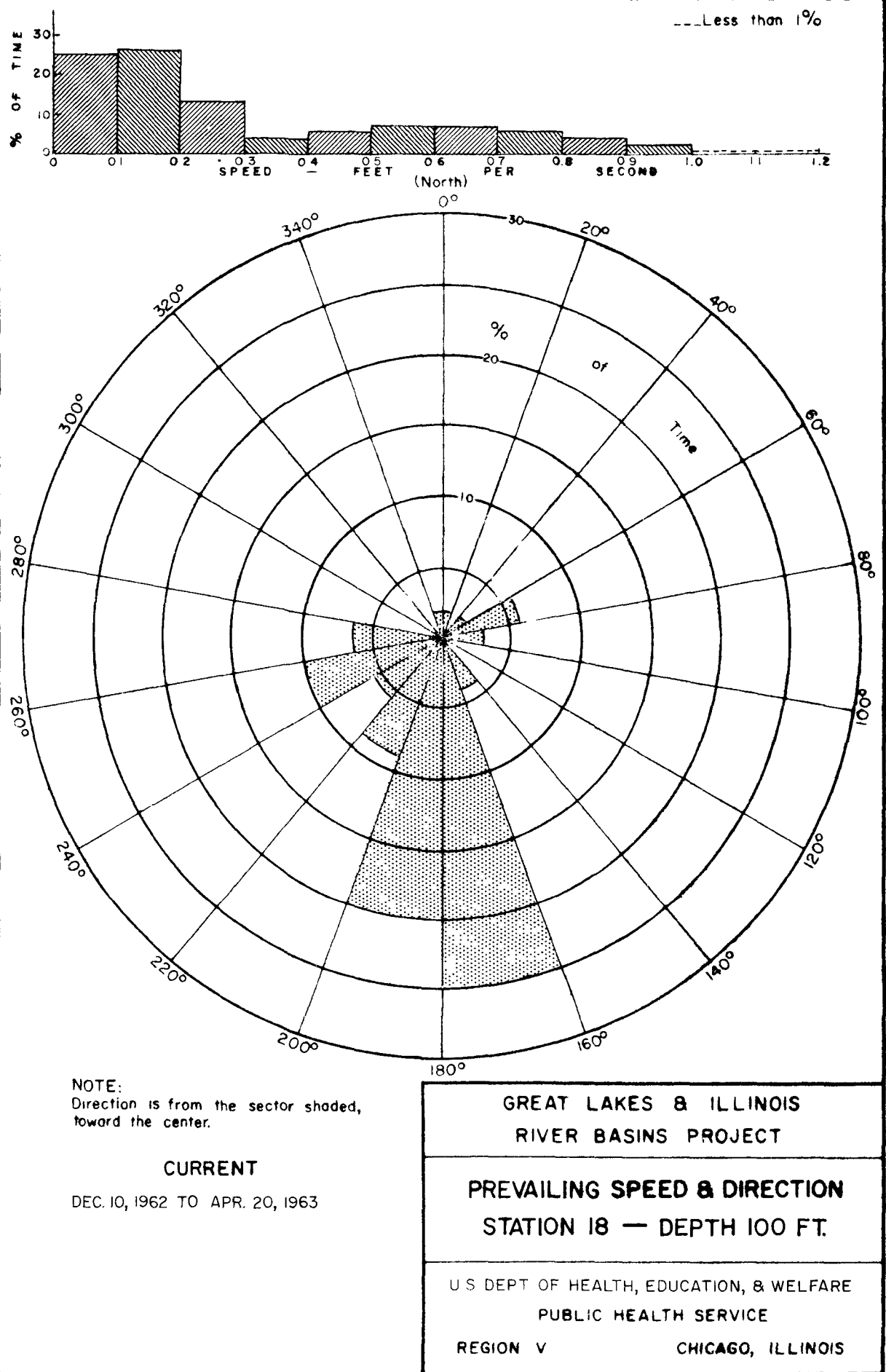
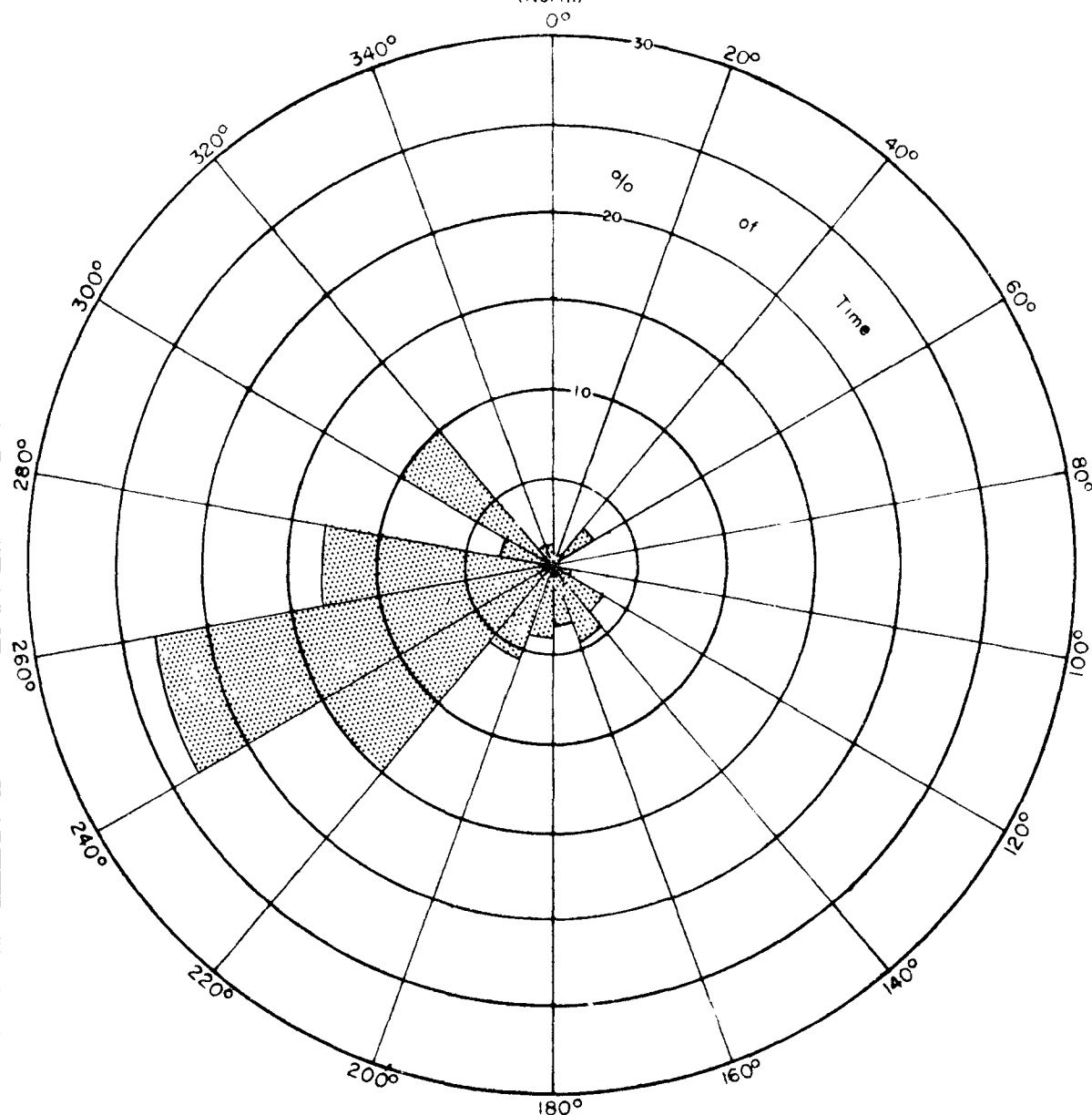
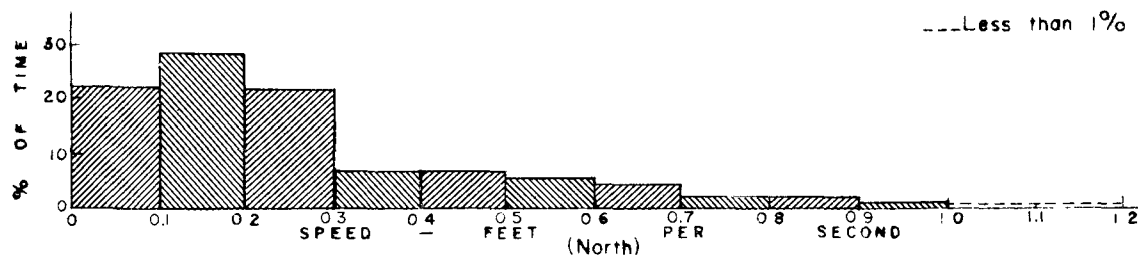


FIGURE II



NOTE:
Direction is from the sector shaded,
toward the center.

CURRENT

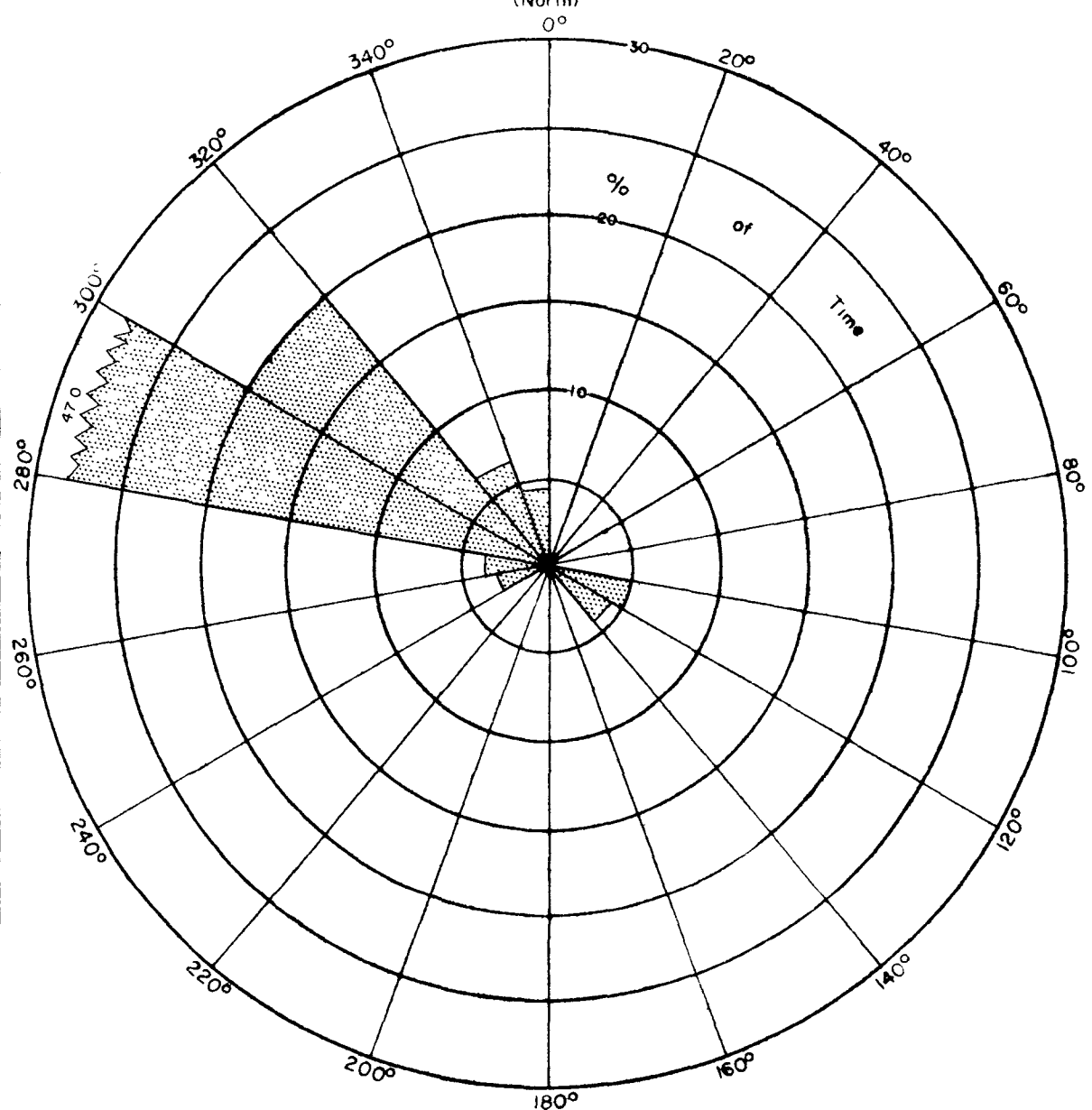
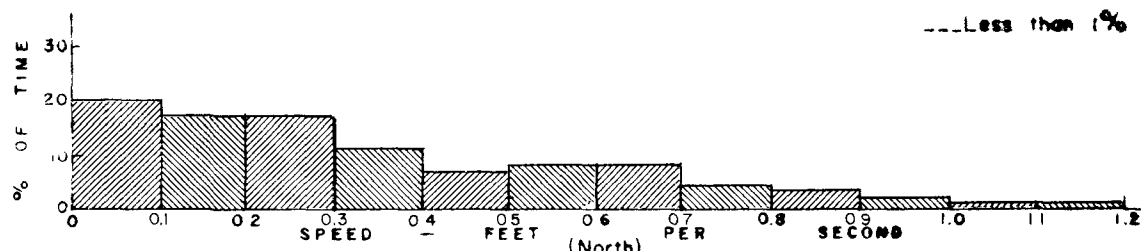
DEC. 5, 1962 TO APR. 20, 1963

GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION
STATION 20-DEPTH 50 FT.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 12



NOTE:
Direction is from the sector shaded,
toward the center.

CURRENT

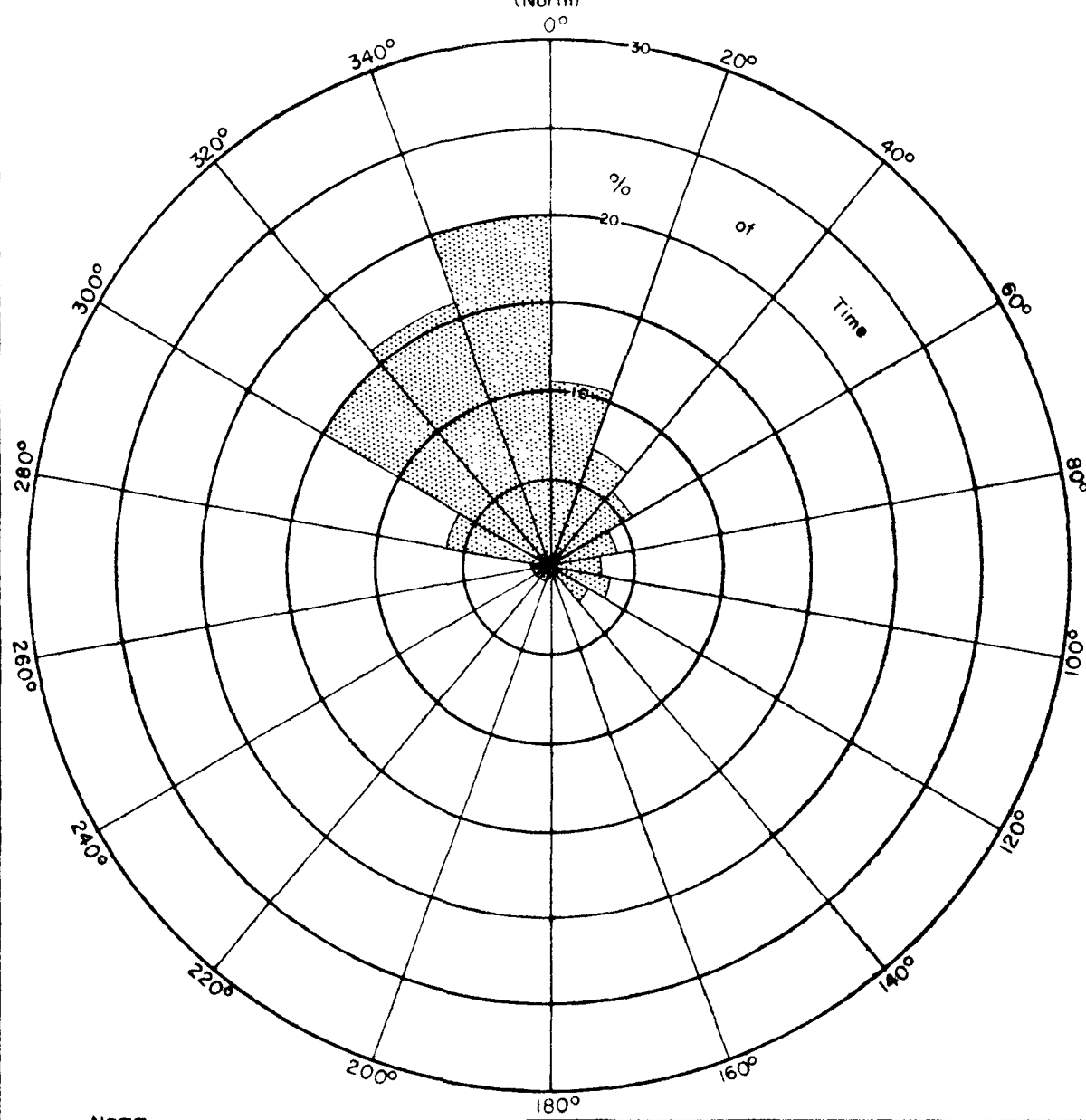
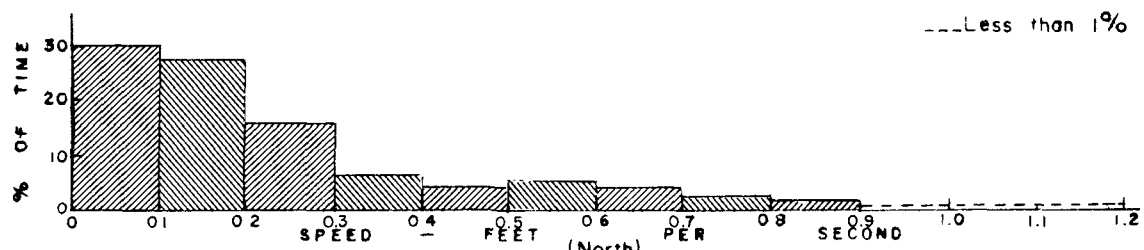
December 3, 1962 to April 20, 1963

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION STATION 20 - DEPTH 100 FT.

U S DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 13



NOTE:
Direction is from the sector shaded,
toward the center.

CURRENT
JAN 25, 1963 TO APR 20, 1963

| | |
|--|-------------------|
| GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT | |
| PREVAILING SPEED & DIRECTION
STATION 20 — DEPTH 300 FT. | |
| U. S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE | |
| ~REGION V | CHICAGO, ILLINOIS |

FIGURE 14

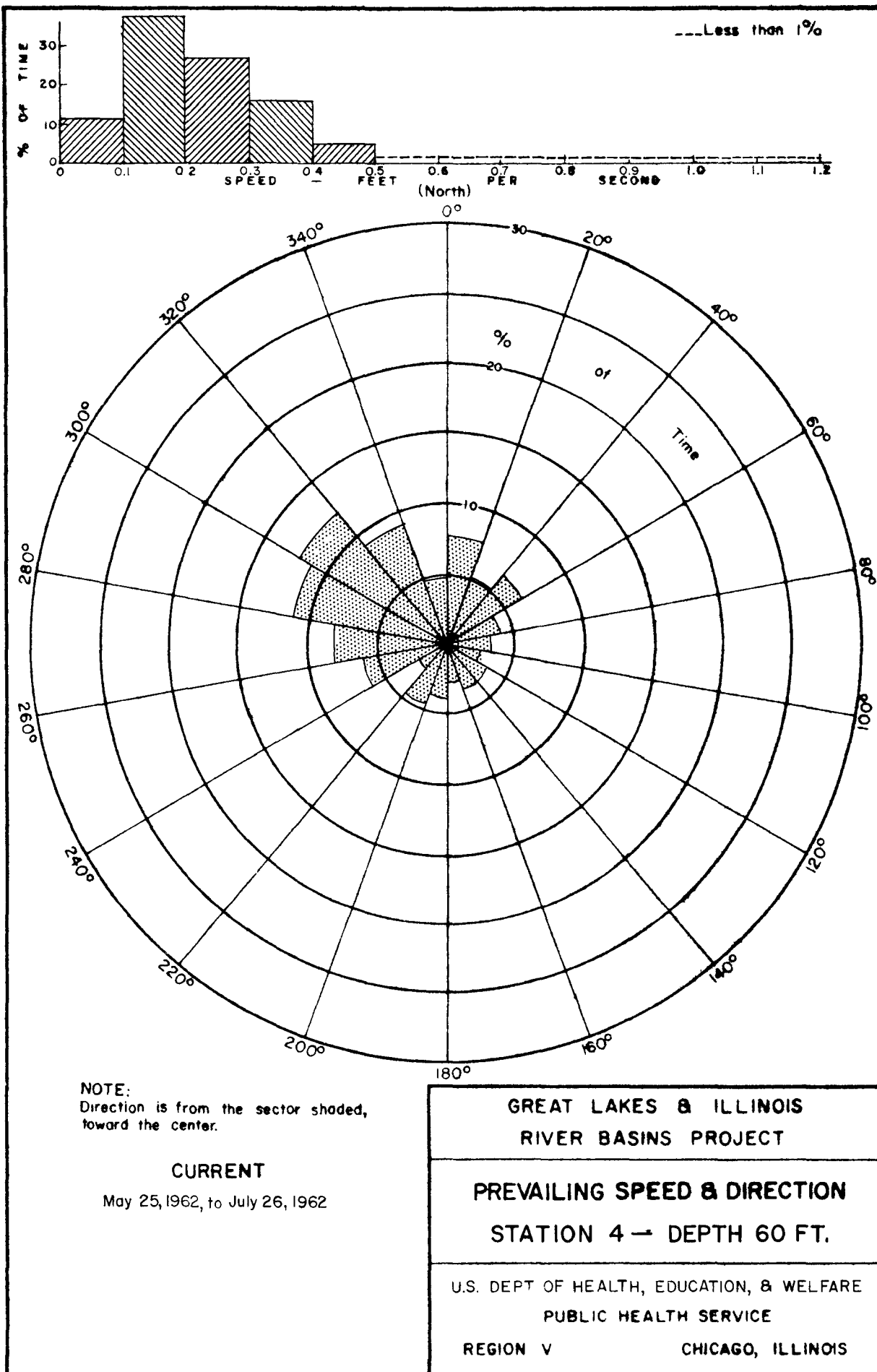
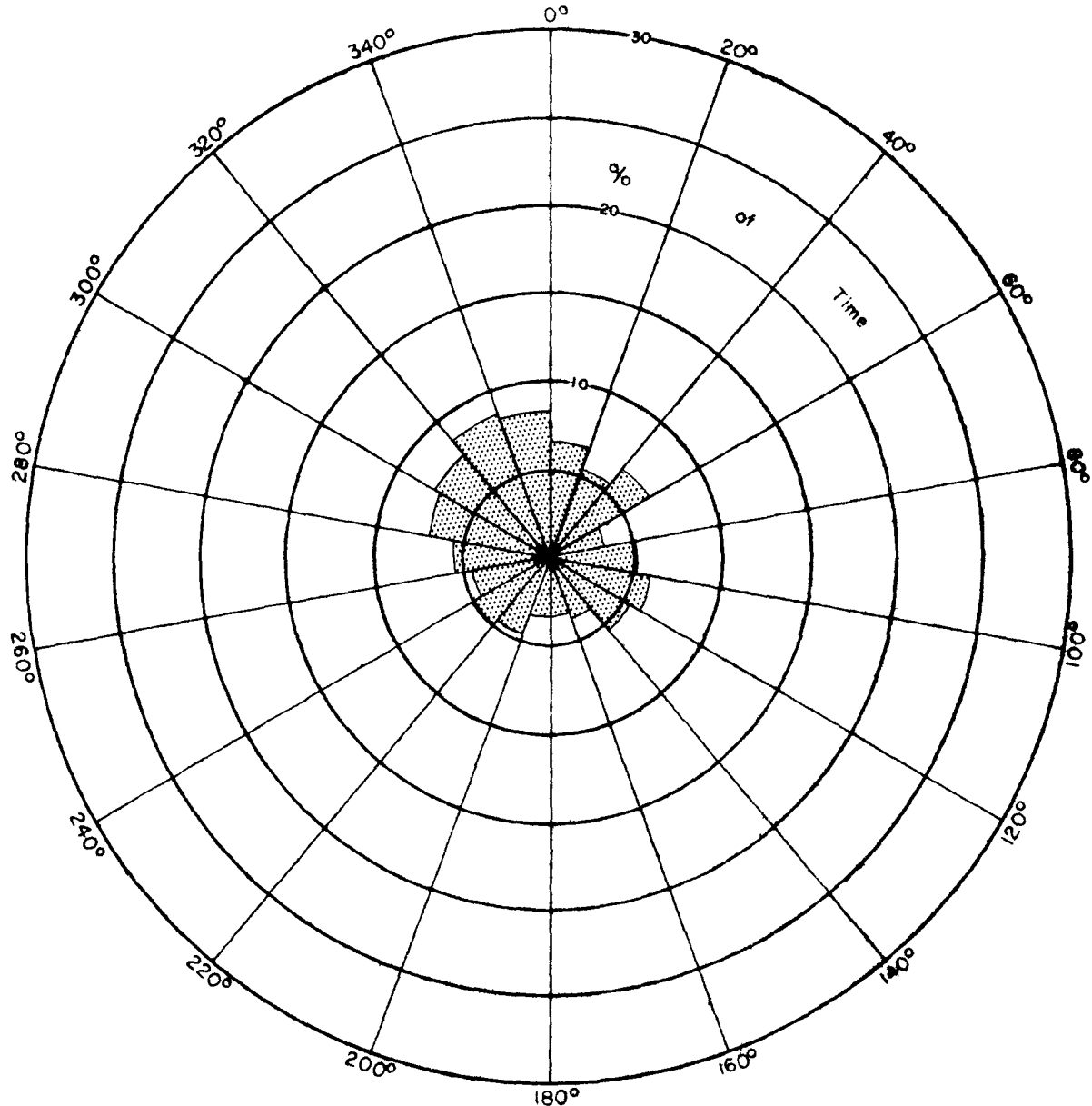
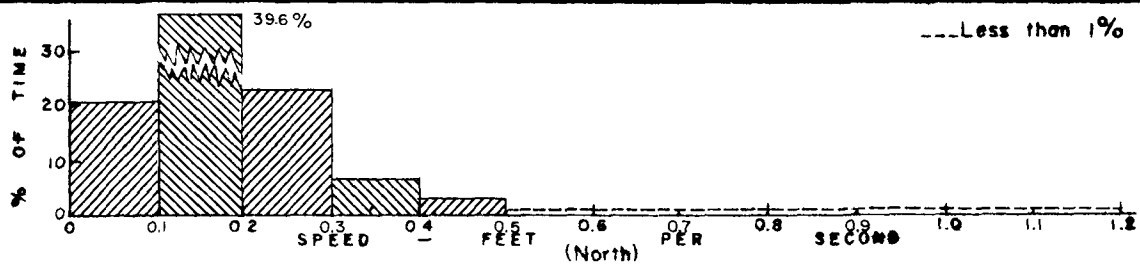


FIGURE 15



NOTE:
Direction is from the sector shaded,
toward the center.

CURRENT

May 25, 1962, to July 26, 1962

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION STATION 4 — DEPTH 90 FT.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE

REGION V

CHICAGO, ILLINOIS

FIGURE 16

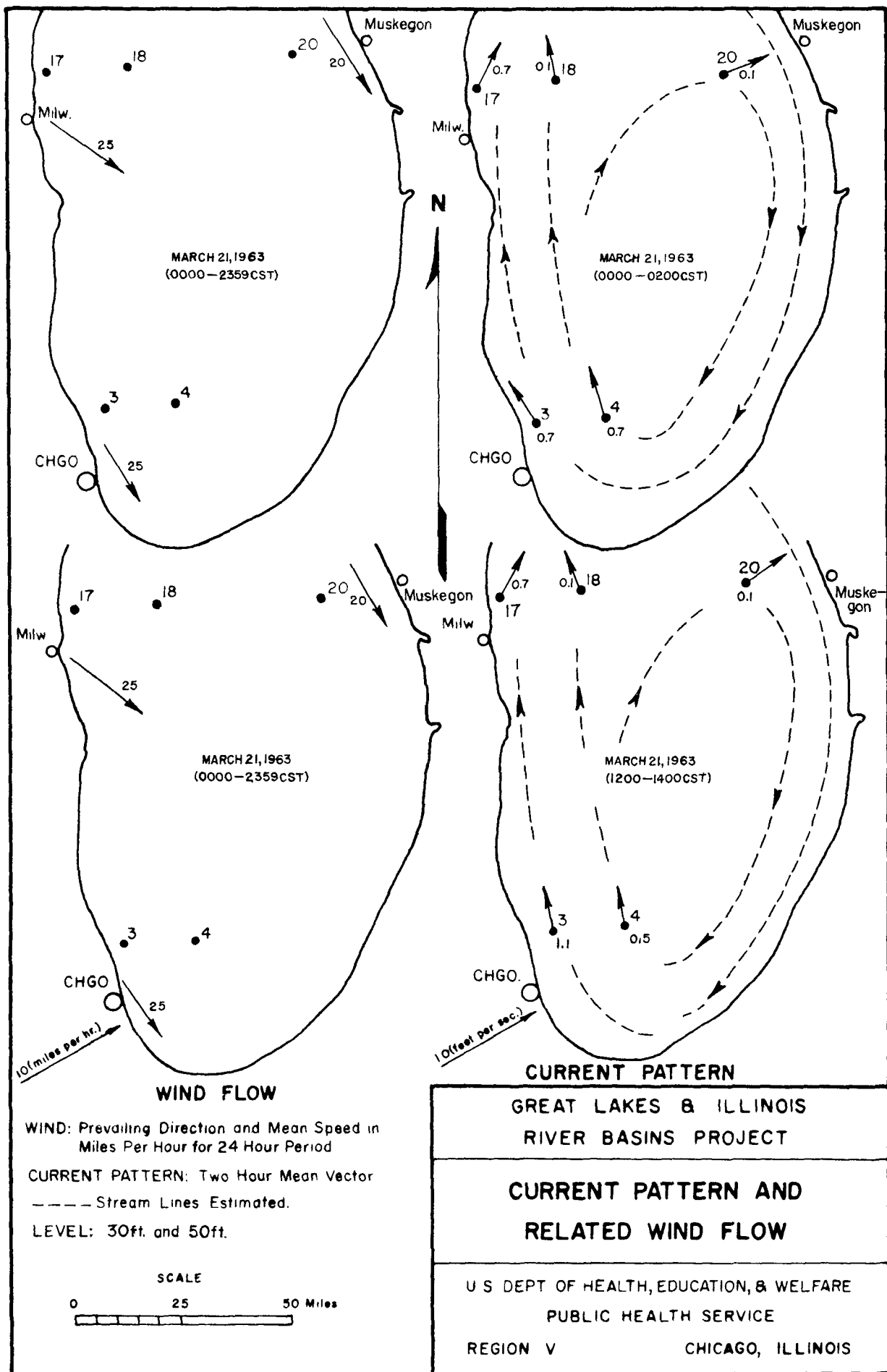


FIGURE 17

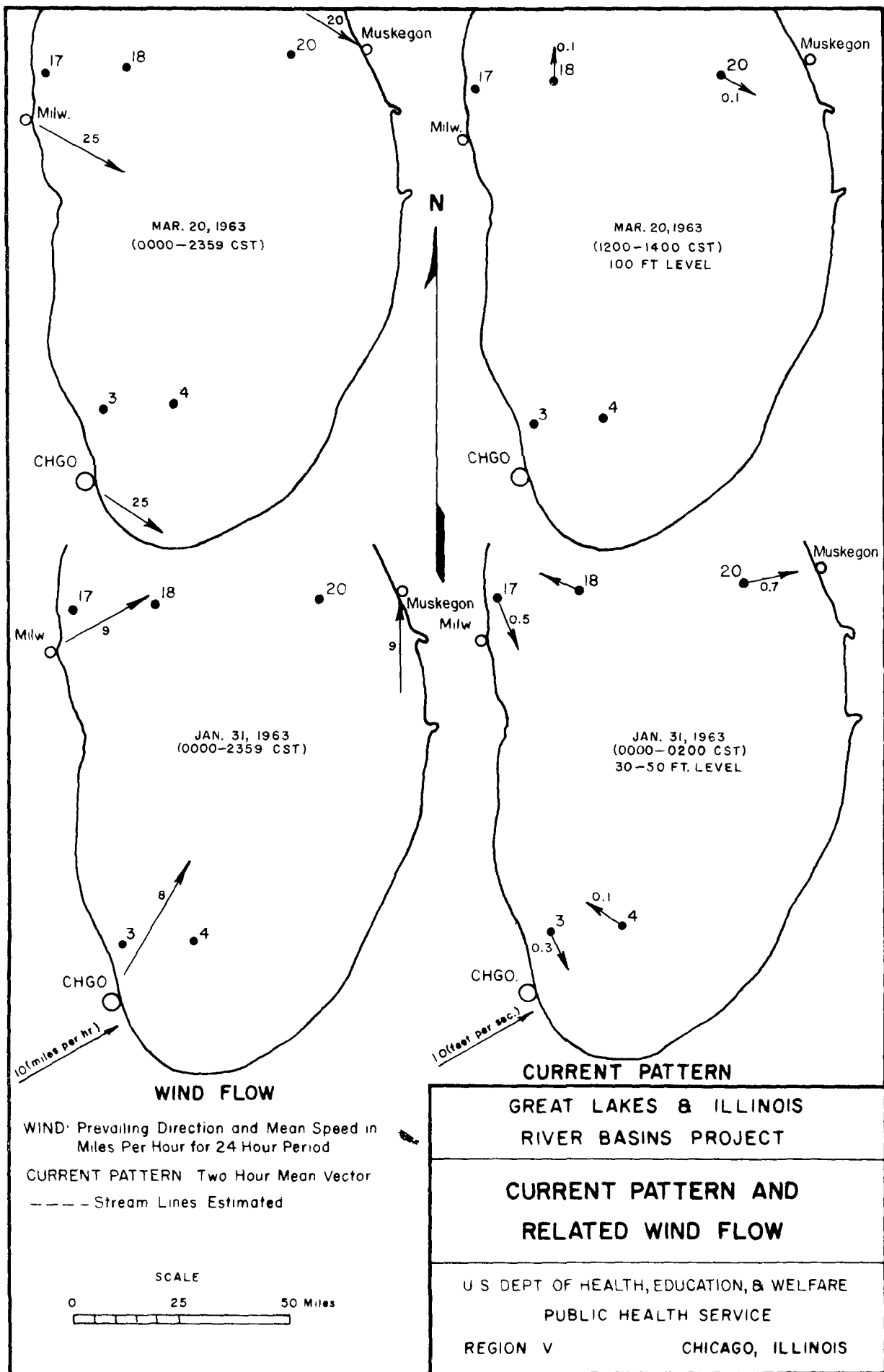


FIGURE 18